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Evaluation of High-Temperature Cast Aluminum–Cerium-Based Alloys

by Taylor W. Cain, Michael Tershakovec, and Jon-Erik Mogonye

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14. ABSTRACT
This study evaluates the high-temperature tensile properties of three development cast aluminum–cerium (Al–Ce)-based alloys with compositions of Al-8.62Ce-2.00Ni-0.64Mn-4.56Mg (DSTE), Al-10.36Ce-3.45Ni-0.80Mn-0.25Sc-0.12Zr (NU), and Al-6.89Ce-7.76Cu-2.30Ni-1.09Mn-1.17Mg (RCOB-Cu-E) in weight-percent. The tensile behavior of the alloys was investigated in as-fabricated and overaged conditions at temperatures ranging from 25 to 350 °C to determine their suitability as potential replacement alloys for conventional 300-series cast aluminum alloys. The results showed moderate-to-low yield strengths of the experimental alloys at room temperature with respect to conventional 300-series alloys. However, alloy DSTE demonstrated excellent retention of mechanical properties at temperatures of 250 and 300 °C. The yield strength of all experimental alloys converged at 350 °C but possessed yield strengths greater than those of 300-series alloys, which demonstrates the promise of Al–Ce-based alloys for high-temperature applications.

15. SUBJECT TERMS
aluminum casting, aluminum alloy, eutectic alloy, aluminum–cerium alloy, Al–Ce, Mechanical Sciences, Sciences of Extreme Materials

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Acknowledgments

We acknowledge the alloy development teams at Northwestern University and The University of Tennessee-Knoxville (UT-K) who developed two of the alloys under investigation in this technical note. The Northwestern team was composed of Dr. Clement Ekaputra advised by Prof. David Dunand under Cooperative Agreement Number W911NF2020292 and W911NF2120199. Contributions to development of the UT-K alloy include Dr. Max Neveau, Elizabeth Heon, Emma Counce, Dr. William Meier, and Dr. Matthew Chisholm advised by Prof. Eric Lass and Prof. Gerd Duscher under Cooperative Agreement Number W911NF2220007. A final acknowledgment goes to David Weiss (formerly of Eck Industries) for his tremendous expertise, guidance, and industry perspective throughout the course of the program.

1. Introduction

Through collaborative efforts with Northwestern University (NU), the University of Tennessee-Knoxville (UT-K), and Eck Industries, the U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) investigated aluminum–cerium (Al–Ce)-based alloys. Extensive investigation of various alloy systems led to the down-selection of three unique alloys for pilot-scale industrial trials with a target of producing an alloy with more superior yield strength than current commercial 300-series Al–Si-based cast alloys at temperatures above 250 °C (Figure 1). The down-selected alloys were chosen based on their ability to leverage multiple strengthening mechanisms. First, the ARL alloy containing Al-Ce-Mg-Ni-Mn relies on the large solid solution strengthening of Mg and minor solid solution strengthening effect of Mn along with the presence of coarsening-resistant $Al_{11}Ce_3$ and Mn-containing phases. This alloy demonstrated excellent yield-strength retention at temperatures above 250 °C with an estimated three times higher in yield strength compared with 300-series cast alloys in this temperature regime.[1]

The NU alloy (Al-10.36Ce-3.45Ni-0.80Mn-0.25Sc-0.12Zr) also relies on the coarsening resistance of $Al_{11}Ce_3$ and Mn-containing phases along with the precipitation strengthening of the $L1_2$ nano phase via the addition of Sc and Zr and solid solution contributions of Mn. This alloy has exhibited exceptional creep resistance and very good long-term stability of the $L1_2$ phase at temperatures of 300 °C or greater in comparison with Ni and/or Mn free Al–Ce alloys with and without Sc and Zr.[2,3] Finally, the UT-K alloy (Al-Ce-Cu-Ni-Mn-Mg) leverages the coarsening resistance of a thermally stable rhombicuboctahedron (RCO) phase present as primary particles or as a fine eutectic phase along with precipitation strengthening of Al–Ce-based nanoprecipitates.[4] The goal of this investigation was to determine the tensile mechanical properties of each down-selected alloy at temperatures up to 350 °C and compare them with the commercial alloys in Figure 1.

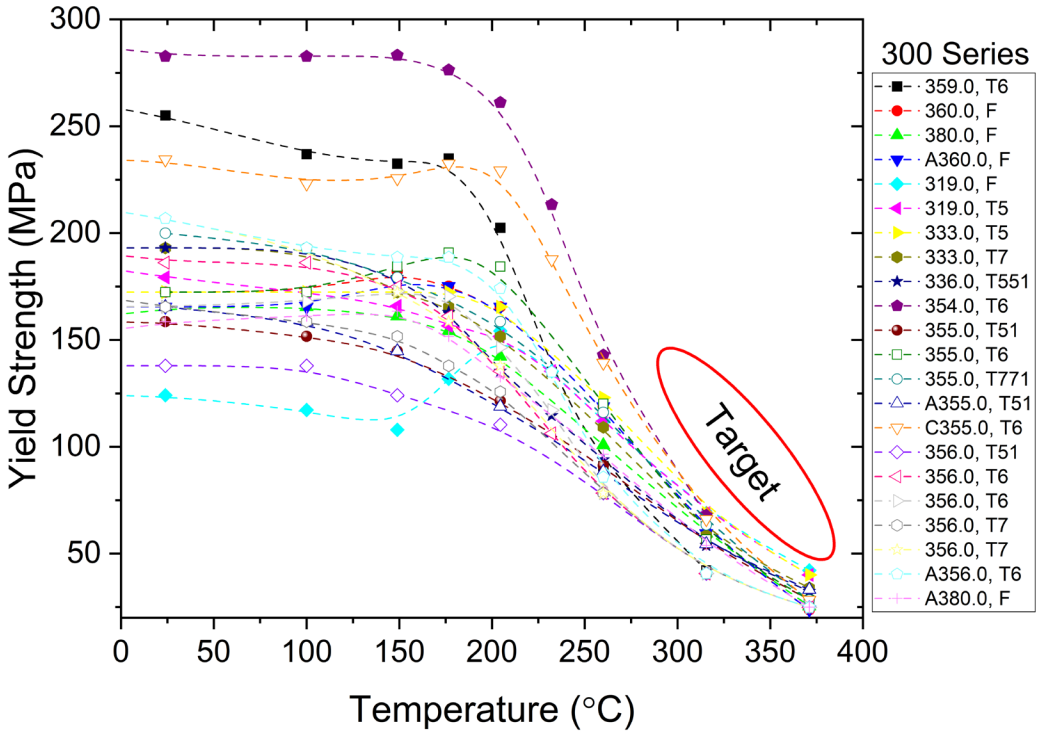

Figure 1. Yield strength vs. temperature for various commercial 300-series cast Al–Si alloys and the target material property zone for this investigation.

2. Experimental

2.1 Materials

Three different alloys were cast whose measured compositions are found in Table 1. A 50-lb heat of each alloy was poured into an ASTM 108/B108M-14[5] tensile bar mold providing a quantity of 12 B108 castings and a total of 24 tensile bars of each alloy. Upon receipt, the round tensile bars were cut out of each casting using a vertical band saw and no further machining was performed prior to tensile testing. A full set of the B108 castings is shown in Figure 2. Alloy RCOB-Cu-E (Al-6.89Ce-7.76Cu-2.30Ni-1.09Mn-1.17Mg) was given a T6 heat treatment by solution treatment at 520 °C for 4 h and then water quenched. The specimens were allowed to naturally age at room temperature for 24 h and were then artificially aged at 325 °C for 4 h and ambient air cooled. The NU alloy was given a T5 heat treatment by heating the as-cast tensile bars for 2 h at 350 °C and ambient air cooled while the DSTE alloy (Al-8.62Ce-2.00Ni-0.64Mn-4.56Mg) was homogenized at 450 °C for 4 h and ambient air cooled to provide an O3 temper. In addition, samples of each alloy were given a further T7 heat treatment by exposing the as-fabricated T5, T6, or O3 tempers at 450 °C for 100 h.

Table 1. Composition of alloys investigated.

Alloy	Al (wt%)	Ce (wt%)	Cu (wt%)	Ni (wt%)	Mn (wt%)	Mg (wt%)	Sc (wt%)	Zr (wt%)
DSTE	Bal.	8.62	. . .	2.00	0.64	4.56	. . .	. . .
NU	Bal.	10.36	. . .	3.45	0.80	. . .	0.25	0.12
RCOB-Cu-E	Bal.	6.89	7.76	2.30	1.09	1.17	. . .	. . .



Figure 2. Full set of B108 castings for the NU alloy with two excess cylinders.

2.2 Hot Tensile Testing

Tensile testing was performed using a 5980 Series Instron load frame with a 3119-616 Instron furnace and 2716-003 Instron mechanical wedge grips with 2703-348 Instron wedge grip inserts. A digital image correlation (DIC) system made by Correlated Solutions was used to measure the strain during testing. Calibration of the DIC system was completed using a 10 × 14 grid. Prior to testing, all specimens were spray-painted with base coat of Rust-Oleum high-heat resistant white protective enamel and speckled with Rust-Oleum high-heat resistant Bar-B-Que Black protective enamel. All bars were preloaded to a force of 75 N and then pulled at a strain rate of 1.52 mm/min. The bars were pulled at room temperature, and 250, 300, and 350 °C. For all elevated temperatures, the bars were allowed to equilibrate to the environmental temperatures for 10 min, once the target temperature was reached. Bars were then preloaded to 100 N and pulled until 10% of the maximum load above 500 N was reached. Tensile bars at each temperature were chosen from different B108 castings to be representative of the entire heat. The yield strength for each test was determined by the 0.2% offset of the linear elastic region of the stress–strain curve while the ultimate tensile strength (UTS) was the maximum stress reached.

3. Results

The representative engineering stress–strain curves for each alloy and heat treatment condition are shown in Figures 3–7. The tensile responses of the DSTE alloy in the homogenized O3 condition and overaged T7 condition are shown in Figures 3 and 4, respectively. At room temperature, DSTE exhibited brittle behavior with negligible plastic deformation in the O3 temper and limited plastic deformation in the T7 temper. Fracture occurred predominantly in the elastic or early yielding regime where only the UTS was determined for DSTE-O3 at the fracture stress. The UTS was substantially higher in the O3 condition (≈182 MPa) compared with the T7 condition (≈144 MPa), while yielding initiated near 128 MPa for the T7 condition. As the temperature increased to 250 °C, DSTE demonstrated notable thermal stability, maintaining virtually identical yield strength (≈130 MPa in O3 temper and ≈123 MPa in T7 temper). In addition, noticeable plastic flow and ductility developed at and above 250 °C owing to thermally activated slip. At 300 °C, the yield strength remained around 100 MPa for both tempers, indicating high resistance to thermally activated softening. Softening due to overageing became pronounced at 350 °C where yield strengths decreased to approximately equal to 65 MPa (DSTE-O3) and approximately equal to 57 MPa (DSTE-T7).

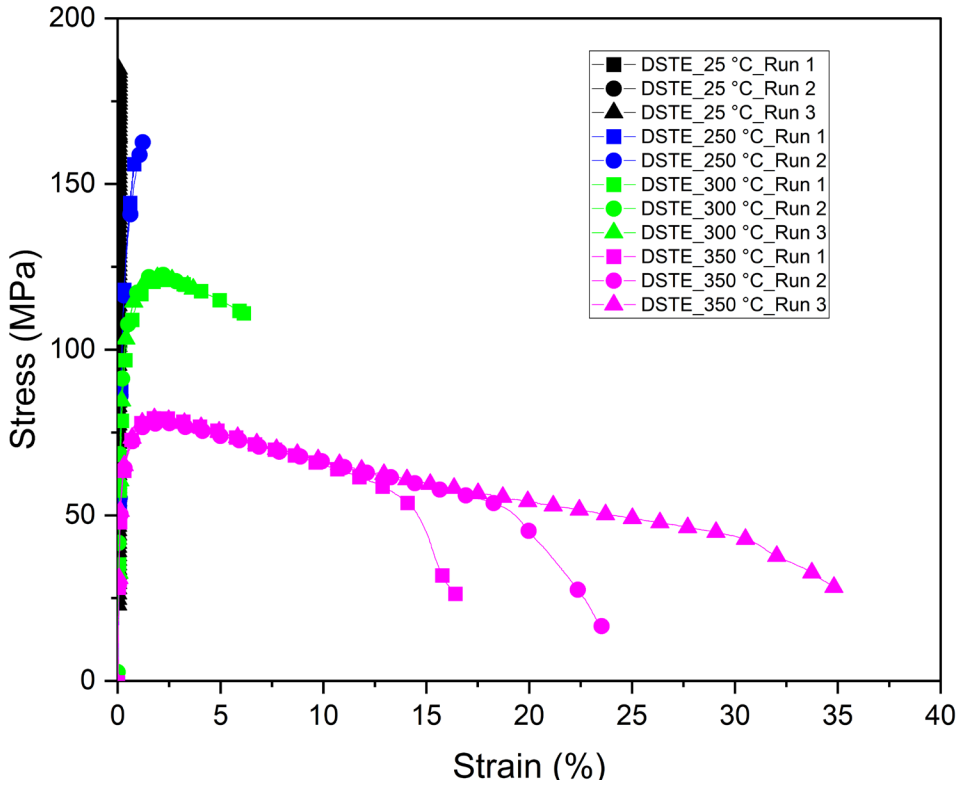

Figure 3. Stress vs. strain curves of DSTE-O3 at 25, 250, 300, and 350 °C.

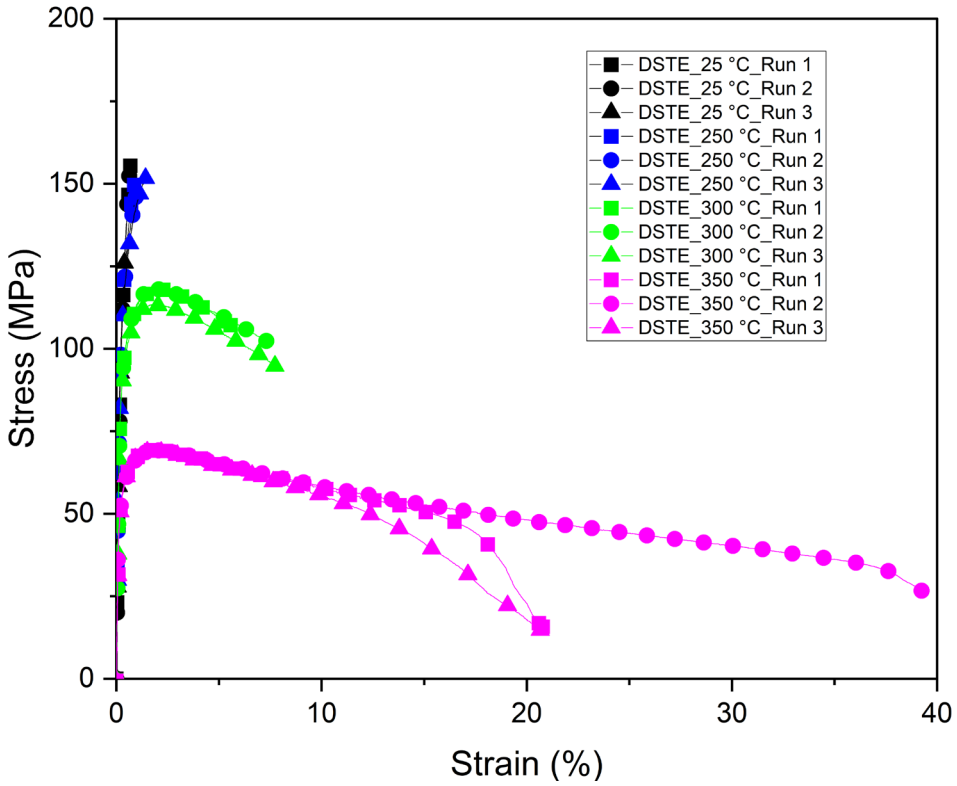

Figure 4. Stress vs. strain curves of DSTE-T7 at 25, 250, 300, and 350 °C.

The engineering stress–strain responses of the NU alloy in the artificially aged T5 condition and overaged T7 condition are displayed in Figures 5 and 6, respectively. Alloy NU-T5 achieved the highest room-temperature strength among all tested alloys exhibiting a yield strength of approximately equal to 162 MPa and a UTS of approximately equal to 212 MPa. The alloy demonstrated measurable work hardening prior to failure in comparison with DSTE at room temperature. Following the overageing thermal exposure, NU-T7 exhibited a moderate reduction in room-temperature yield strength (≈132 MPa) and UTS (≈176 MPa), while displaying increased ductility and variation across individual castings. Unlike DSTE, the yield strength of the NU alloy experienced a sharp decrease between room temperature and 250 °C, falling from approximately equal to 162 MPa to approximately equal to 76 MPa for NU-T5 and from approximately equal to 132 MPa to approximately equal to 75 MPa for NU-T7. However, the strength stabilized between 250 and 350 °C. At 350 °C, NU-T5 retained a yield strength of 63 MPa and UTS of approximately equal to 102 MPa.

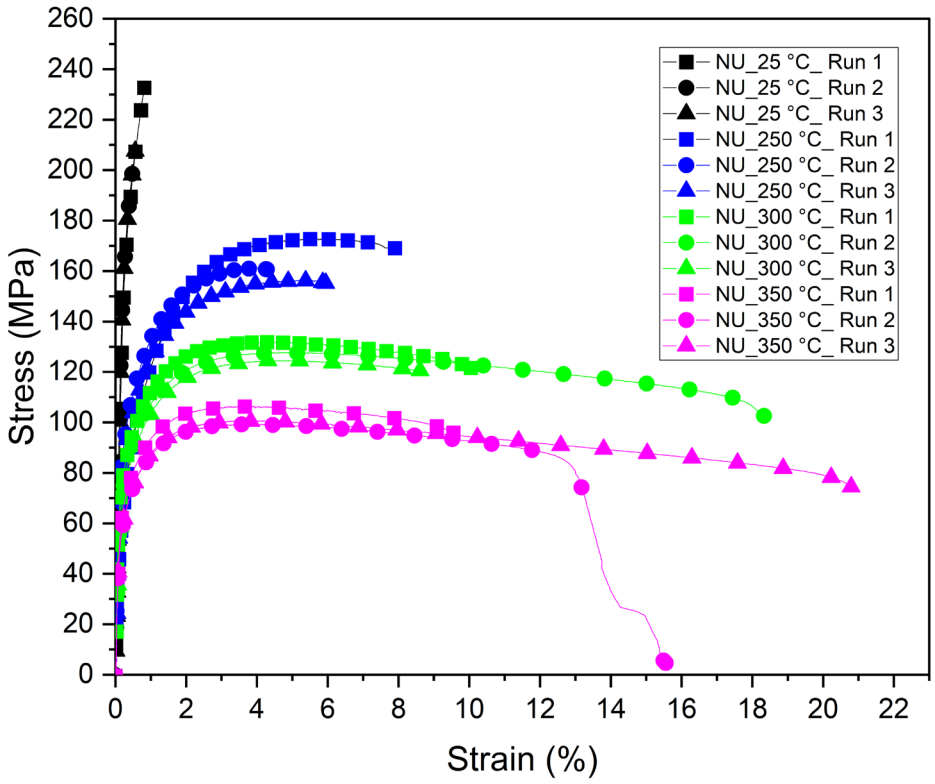

Figure 5. **Stress vs. strain curves of NU-T5 at 25, 250, 300, and 350 °C.**

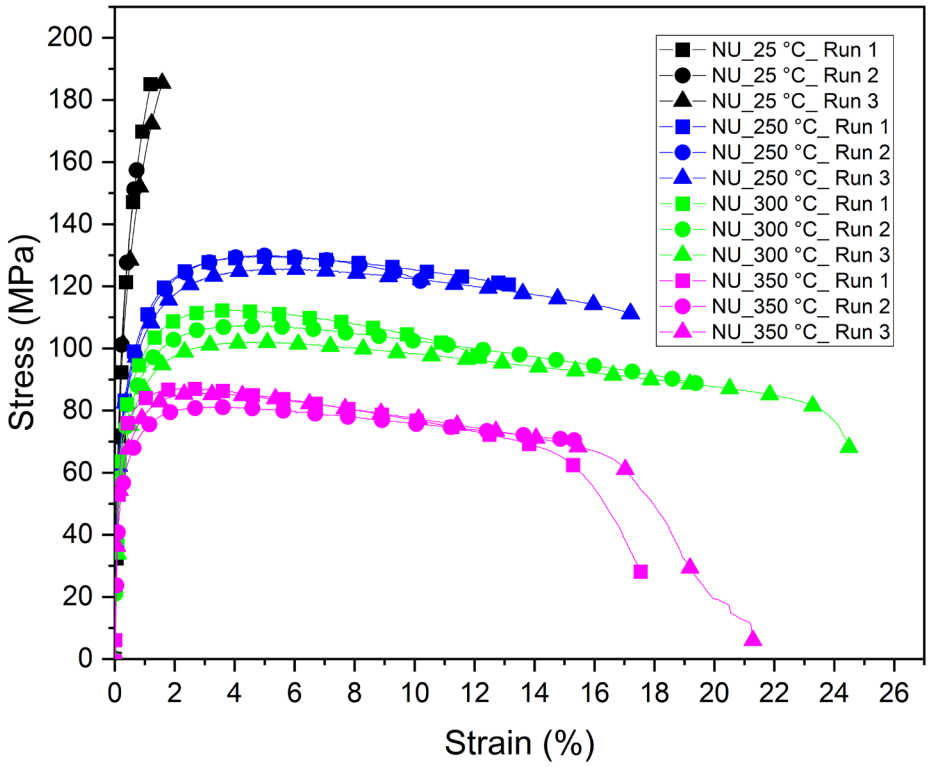

Figure 6. **Stress vs. strain curves of NU-T7 at 25, 250, 300, and 350 °C.**

The tensile behavior of RCOB-Cu-E in the peak-aged T6 condition is presented in Figure 7, while the T7 temper was unable to be tested prior to the end of the program. RCOB-Cu-E-T6 exhibited a balanced combination of yield strength (≈130 MPa) and UTS (≈169 MPa) with minimal ductility at room temperature. At 250 °C, the alloy maintained a yield strength of approximately equal to 103 MPa and a UTS of approximately equal to 124 MPa, which was superior to NU-T5 at the same temperature. With further temperature increases to 300 and 350 °C, steady thermal softening occurred, reducing the yield strength and UTS to approximately equal to 61 MPa and approximately equal to 83 MPa, respectively, which was accompanied by increased plastic elongation.

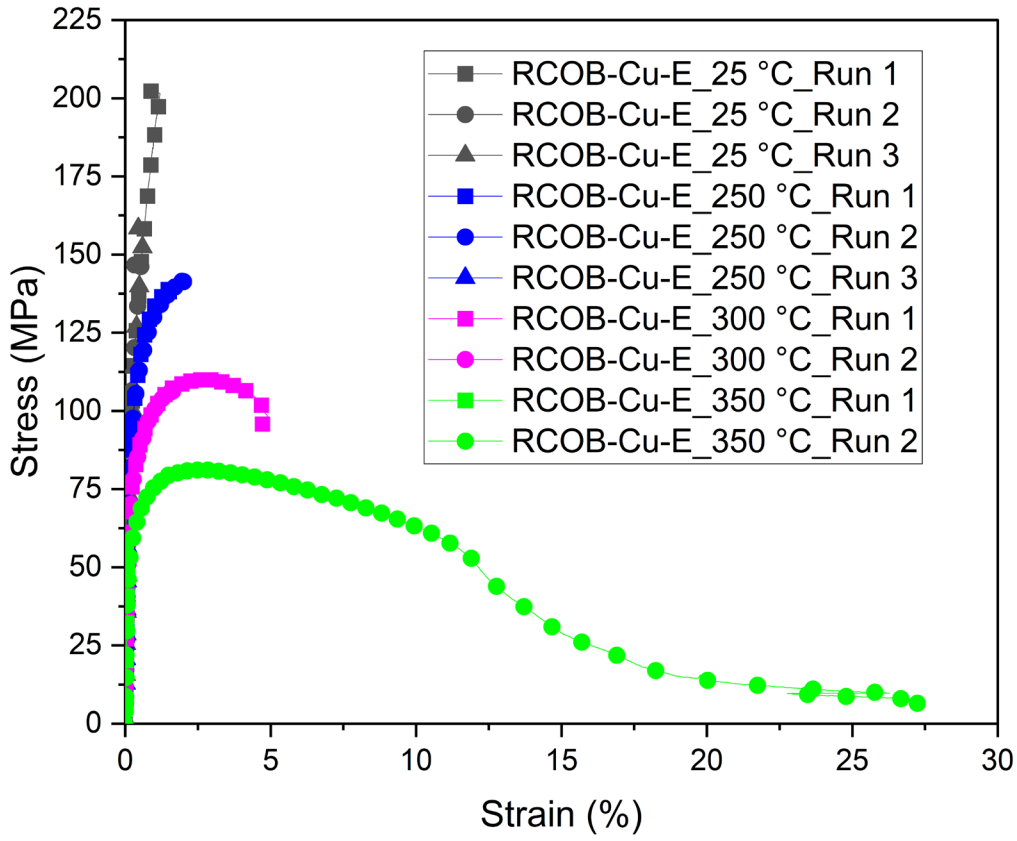

Figure 7. Stress vs. strain curves of RCOB-Cu-E-T6 at 25, 250, 300, and 350 °C.

A direct comparison of the temperature-dependent tensile properties across all alloys and temper conditions tested herein is illustrated in Figure 8. Comparison of the yield strength in Figure 8a shows that DSTE possessed the highest yield strength at 250 and 300 °C in the O3 temper and after overageing, while NU-T5 possessed the highest room-temperature yield strength. However, the NU alloy after overageing had a similar yield strength to overaged DSTE at room temperature. This was also true at 350 °C where all alloys had a similar yield strength. In

contrast, the NU alloy possessed the highest UTS across all temperatures in the T5 and overaged conditions, which indicates the best strain hardening of all alloys.

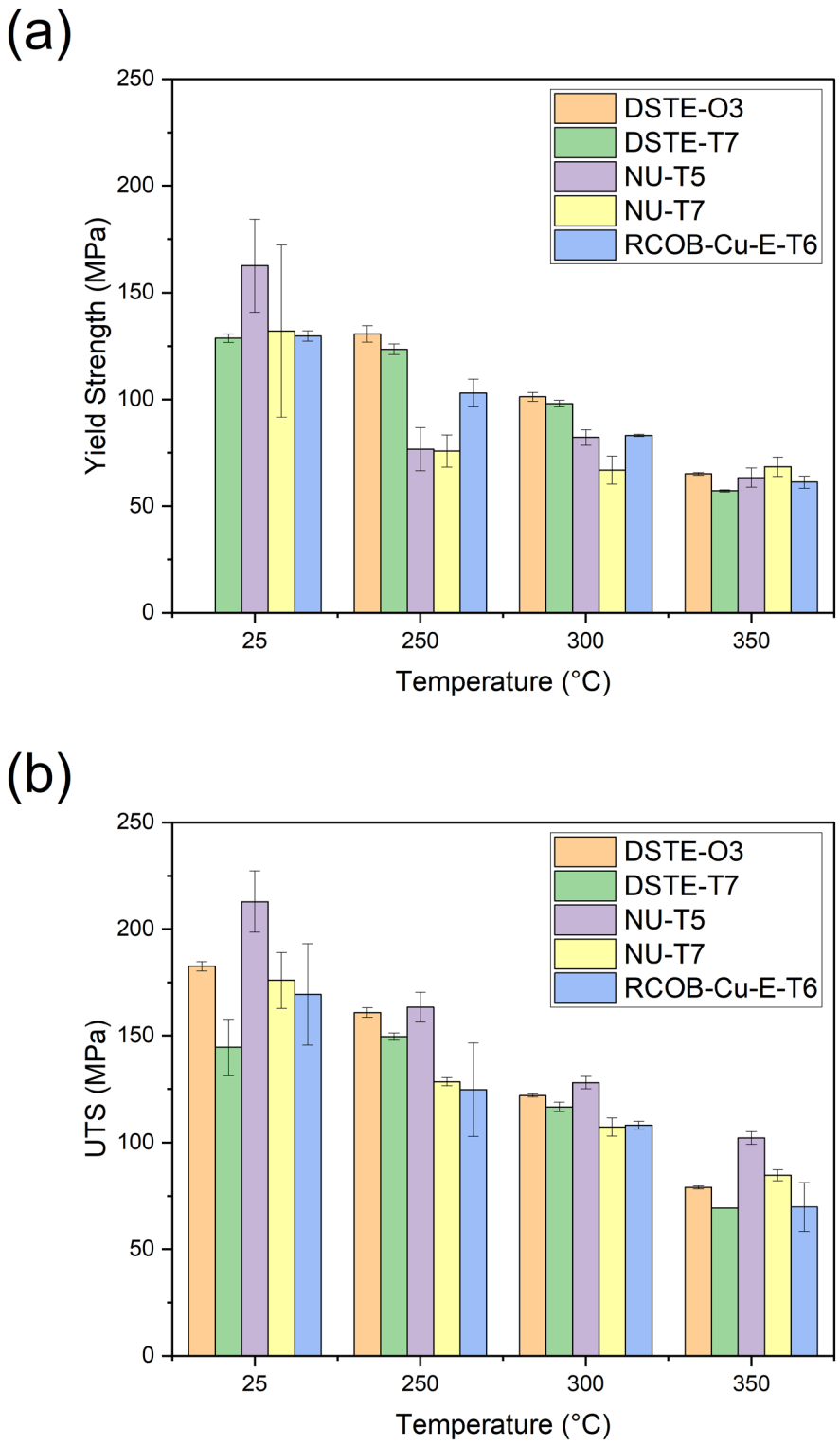

Figure 8. Summary plots of the (a) yield strength and (b) UTS for all alloys at 25, 250, 300, and 350 °C.

A critical benchmark for evaluating the developmental pilot alloys is their yield strength relative to current commercial alloys. A plot comparing the yield strength of pilot alloys with commercial 300-series Al–Si alloys is shown in Figure 9. The pilot cast alloys showed yield strengths in the bottom 50% of 300-series alloys at room temperature with NU-T5 having the highest yield strength. However, pilot alloys DSTE and RCOB-Cu-E demonstrated very competitive yield strengths at 250 °C with only A354.0-T6 and C355.0-T6 having a higher yield strength than DSTE-O3. In addition, pilot alloys did not experience as large of a reduction in yield strength as commercial 300-series alloys above 250 °C where most commercial alloys possess a significant reduction in yield strength. At 300 °C, DSTE in both conditions had a higher yield strength than all commercial alloys with all pilot alloys having a yield strength greater than commercial 300-series alloys at 350 °C.

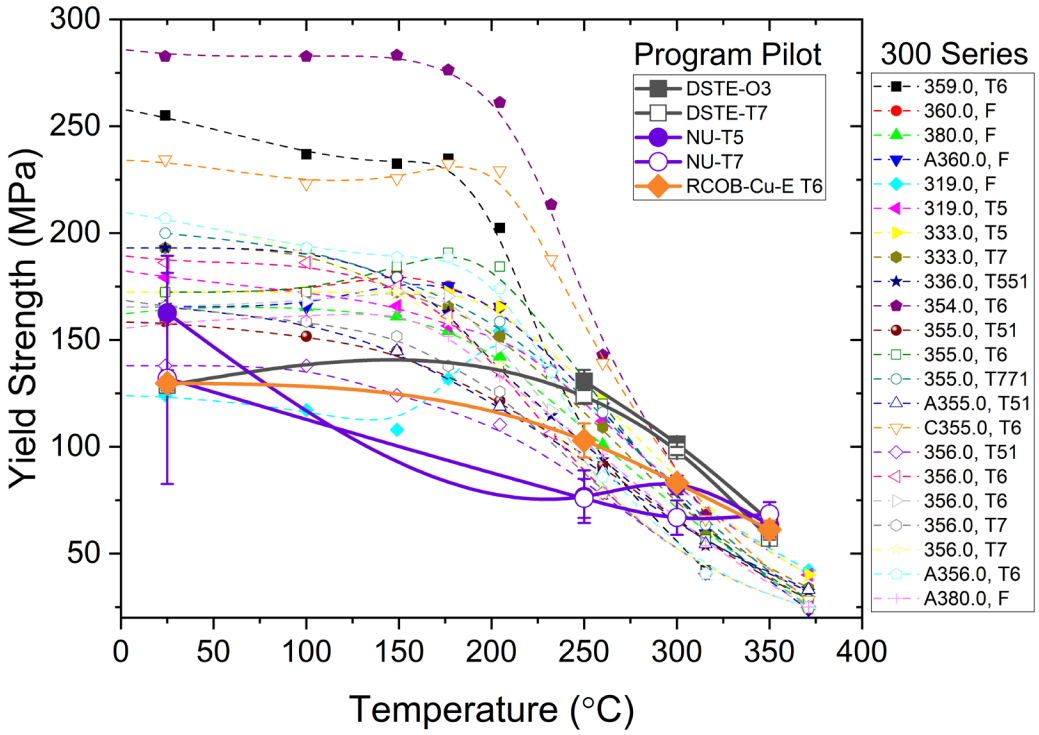

Figure 9. Comparison of the yield strength as a function of temperature for alloys in this investigation with commercial cast Al–Si alloys. Commercial yield strengths were taken from the ASM handbook.[6]

4. Conclusions

The tensile behavior of three developmental cast Al–Ce alloys were investigated from room temperature up to 350 °C in the as-fabricated condition and after being subjected to an overageing thermal exposure of 450 °C for 100 h. Alloy DSTE provided the highest best retention of mechanical properties after the overaged heat treatment, and also had the highest yield strength at temperatures above 250 °C while the yield strength of all alloys converged at 350 °C.

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List of Symbols, Abbreviations, and Acronyms

Al	Aluminum
Al–Ce	Aluminum–Cerium
ARL	Army Research Laboratory
ASTM	American Society for Testing and Materials
Bal.	Remaining balance
at%	Atomic Percent
Ce	Cerium
Cu	Copper
DEVCOM	U.S. Army Combat Capabilities Development Command
DIC	Digital Image Correlation
DSTE Alloy	Al-8.62Ce-2.00Ni-0.64Mn-4.56Mg
FWHM	Full Width at Half Maximum
m	Schmid Factor
Mg	Magnesium
Mn	Manganese
Ni	Nickel
NU	Northwestern University
NU alloy	Al-10.36Ce-3.45Ni-0.80Mn-0.25Sc-0.12Zr
RCO	Rhombicuboctahedron
RCOB-Cu-E	Al-6.89Ce-7.76Cu-2.30Ni-1.09Mn-1.17Mg
Sc	Scandium
SYS	Shear Yield Strength
UT-K	The University of Tennessee-Knoxville
UTS	Ultimate Tensile Strength
wt%	Weight-Percent
Zr	Zirconium

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