N. High-Temperature Aluminum Alloys

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Objective

- Develop high-temperature aluminum alloys with adequate properties and shape capability for turbocharger compressor wheels and housing applications.

Approach

- Develop ternary-phase compositions by modeling the equilibrium phase diagram, making castings, and evaluating the properties of alloys identified.
- Perform physical and mechanical property measurements on specimens provided by the National Aeronautics and Space Administration (NASA) and by Eck Industries to characterize the material and determine the optimal properties attainable by this method.
- Evaluate a nanophase particulate-reinforced aluminum alloy patented by Chesapeake Composites, Inc.

Accomplishments

- Accurately predicted and verified the binary-phase diagrams of Al-Y and Al-Yb using ThermoCalc.
- Studied the age-hardening behavior in NASA 388-T5 alloy. The improvement in high-temperature strength of the NASA 388 alloy was found to be not significant enough to pursue further.
- Demonstrated impressive high-temperature tensile strength, fatigue strength, and thermal stability with the dispersion-strengthened composite (DSC) material.

Future Direction

- Use ThermoCalc to generate the Al-Y-Yb ternary system and identify optimal compositions for casting trials and material property characterization.
- Conduct fatigue tests, creep tests, notch sensitivity tests, and machinability studies of DSC material.
- Fully characterize the DSC material

Introduction

The new emission requirements for diesel engines mandate that the turbocharger compressor be operated at a significantly higher temperature and pressure. This condition makes standard castable aluminum alloys unusable as new-generation turbocharger materials because their strength deteriorates at elevated temperatures. Therefore, there is a need to develop high-strength, high-temperature aluminum alloys, which will replace these standard alloys. Work at Cummins has identified three potential paths to improve the high-temperature strength and fatigue resistance of aluminum casting alloys. These paths have been partially investigated under cooperative agreement DE-FC05-97OR22582. Each path showed some promise, and further work is needed to determine the useful applications.

Approach

The scope of work in the program covers the investigation of three different paths for providing strength retention in aluminum alloys at high temperatures. Path 1 uses a ternary-phase aluminum alloy using rare earth metals to provide precipitate size control and stability. Limited information on these alloys indicates high-temperature strength and stability; however, the predicted cost of the alloy is high. Additional work was performed to determine if there are other rare earth (or other metal) elements that produce beneficial properties at a reasonable cost. The main goal of this path is to generate the phase diagram of Al-Y-Yb (aluminum-yttrium-yterrbium), using ThermoCalc software. Since there are very few published data and assessments on these rare-earth elements, a prudent approach demands that a systematic investigation be carried out. Path 2 uses a conventional aluminum alloy, which has been chemically modified by a process developed at NASA–Huntsville. The elevated-temperature properties reported by NASA are attractive, but Cummins prefers to use an alloy with a lower silicon content. Eck Industries purchased the license for the NASA-developed technology for high-silicon casting alloys and has expanded the range to include conventional low-silicon casting alloys. Limited testing of these modified conventional low-silicon alloys at Cummins has not shown the property improvement anticipated. Currently, NASA 388-T5 alloy is being evaluated to characterize the material and to determine possible process improvement. Path 3 uses a particulate-loaded aluminum alloy patented by Chesapeake Composites. The nanophase particulates at 50 vol % provided adequate high-temperature strength in early experiments; however, the particulate-loaded alloy could only be forged or squeeze cast, so its complex-shape capability was limited. The mechanical behavior of this DSC material is being fully characterized. Casting modifications will be investigated to determine the shape capability for the alloy.

Results

Path 1: Ternary-Phase Aluminum Alloy Development

In the previous report, the binary-phase diagrams of Al-Fe and Al-Mn and a ternary-phase diagram of Al-Fe-Mn were generated using ThermoCalc. The versatility of the software has been clearly demonstrated in the plotting of the phase diagrams. A major aspect of this project is to be able to examine the minute details of any region of interest, which happens to be the aluminum-rich region of the phase diagram. This type of plot simplifies the task of accurately determining the limits of the phase fields in the aluminum-rich corner (or any region of interest) of the phase diagram

Although the software features a wide spectrum of thermodynamic models, databases, and modules, it requires accurate assessment of the elements in order to perform phase equilibrium/diagram calculations. The Al-Y-Yb alloy poses a peculiar challenge, because there has been limited assessment of rare earth elements, especially alloys containing Yb. Although it is not presented, an extensive literature search has been conducted on the thermodynamic assessment of Y and Yb elements. In spite of this fundamental problem, the binary-phase diagrams of Al-Y and Al-Yb have been generated (using ThermoCalc) and validated. Figures 1 and 2 present the phase diagrams of Al-Y and Al-Yb, respectively.

With the prediction of Al-Y and Al-Yb systems, work will begin on predicting the Al-Y-Yb ternary system. Upon deciding on the actual composition of interest, a material supplier will be asked to cast a prototype of the material. A detailed characterization of the material will be carried out at the Florida A&M University–Florida State University College of Engineering. Microcharacterization of the material will rely on scanning electron microscopy

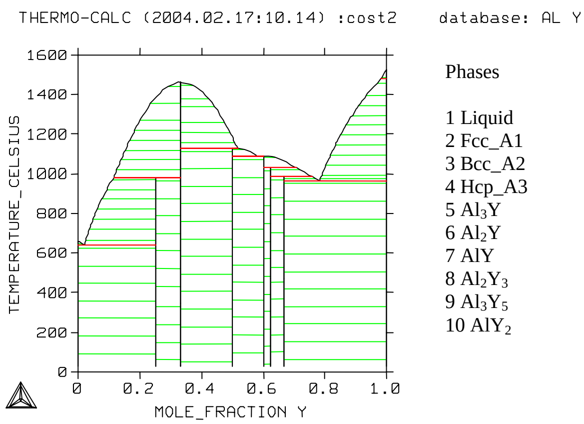

Figure 1. The Al-Y binary phase diagram generated using ThermoCalc.

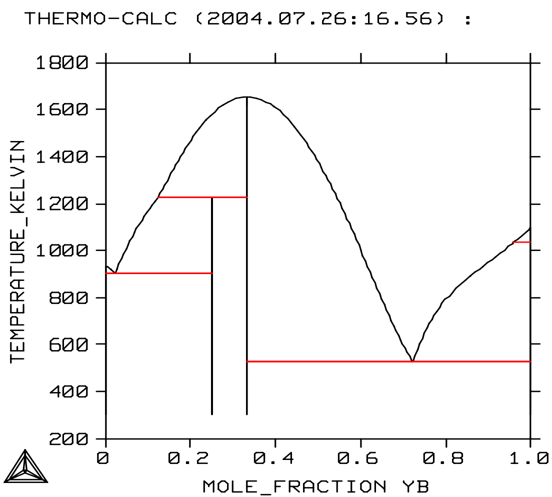

Figure 2. The Al-Yb binary phase diagram generated using ThermoCalc.

(SEM) and transmission electron microscopy (TEM), while the mechanical properties will be evaluated by tensile tests.

Path 2: NASA 388-T5 Aluminum Alloy

The microstructure of 388-T5 Al alloy with NASA modification was characterized. The results indicate that compositional modification leads to some refinement in the size of the silicon particles. A variety of coarse precipitates—$Cu_2Mg_8Si_6Al_5$, $(Cu,Fe,Mn,Ni,V)_3Si_2Al_{15}$, $(Cu,Ni)_2Al$ and $CuAl_2$—were observed. The aluminum matrix was dominated by the presence of plate-shaped precipitates of the metastable θ' phase. These precipitates appear to be mainly responsible for the strengthening. In addition, very fine spherical precipitates having the $L1_2$ structure and presumably the $Al_3(Ti,Zr)$ chemistry were noted. Figure 3 shows the SEM microstructure of NASA 388-T5 alloy.

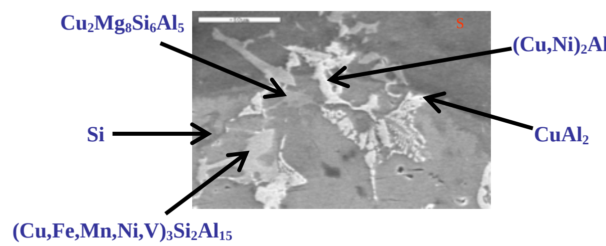

Figure 3. SEM micrograph showing microstructure of the NASA-modified 388 T5 alloy. Several indicated coarse intermetallic precipitates can be noted.

The tensile strength of the thermally soaked and unsoaked NASA 388-T5 material increased slightly from room temperature and reached a peak at 300°F, after which it dropped almost linearly with the increase in temperature. The fracture morphology correspondingly changed from brittle to ductile/dimpled rupture, and microvoids containing second-phase particles in their interior were present. Thermal soaking at high temperatures for times up to 500 hours led to some degradation of the tensile properties.

Extensive mechanical tests were conducted on the NASA 388-T5 and T6 alloys. Tests included elevated-temperature tensile tests and rotating beam fatigue tests of samples, with or without long-term thermal soaking. Test results were compared with those of the current production materials, C355-T61 and 354.0-T61 alloys. A slight improvement in the tensile strength was realized only at test temperatures above 300ºC for the NASA 388-T5 alloy, compared with the strength of the current materials. The degree of improvement was deemed to be insignificant compared with the further development needed for the new casting process and prototype trials. The decision was made to discontinue the evaluation work for the NASA 388-T5 alloy for turbocharger application.

Path 3: Particulate-Reinforced Alloy

This task involves a nanophase particulate-loaded aluminum alloy patented by Chesapeake Composites. A patented, low-cost, liquid metal infiltration process is used to produce a billet form ready for secondary operations. This composite material combines the enhanced elevated-temperature strength, toughness, and ductility of dispersion-strengthened alloys with the stiffness and low coefficient of thermal expansion of metal matrix composites. It is claimed that this composite can be readily turned using tungsten carbide tooling and drilled and tapped using high-speed steel tools. Potential applications include pistons, compressor wheels, and engine components.

As-infiltrated billets of the DSC with a 40 volume fraction of nanoscale Al_2O_3 particles in either 1090Al matrix or 2024Al matrix were supplied by Chesapeake Composites for testing. Tensile specimens were prepared from the billets and thermally soaked at 204, 260, 316, and 371°C for 500 hours prior to testing. Figure 4 shows the tensile test results for the DSC material at elevated temperatures. The tensile strength of the DSC material decreased nearly linearly from ~58 ksi at room temperature to ~20 ksi at 371°C, the latter value being impressively high for an aluminum alloy. It was noted that essentially no reduction in the tensile strength of the DSC material was observed. This indicated that the DSC material exhibited a very good thermal stability even after long-tem usage at high temperatures. The properties of the 2024Al-DSC material are comparable to those of the 1090Al-DSC material over the entire temperature range, suggesting that the second-phase precipitates expected in the former have little or no influence and that the properties are dominated by the presence of a high volume fraction of submicron-scale Al_2O_3 particles.

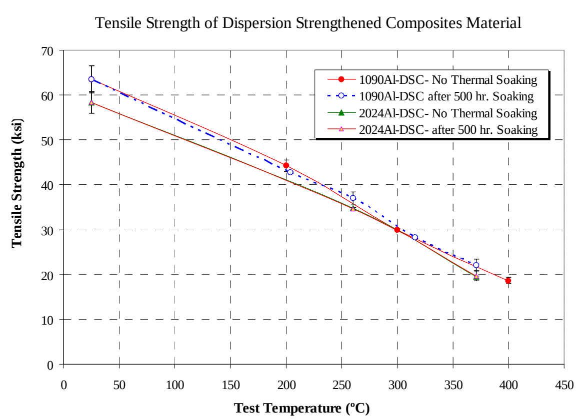

Figure 4. Tensile strength of DSC material at elevated temperatures.

Rotating beam fatigue tests of 2024Al-DSC and A354-T6 alloy were conducted at 260°C (500°F). Figure 5 shows the fatigue test results. The fatigue

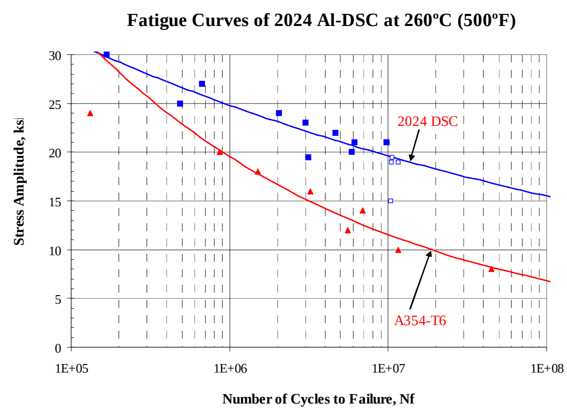

Figure 5. Rotating beam fatigue strength of DSC material and 354-T6 alloy at 260°C.

strength of the 2024Al-DSC material was determined to be far superior to that of A354-T6 alloy, which is a premium aluminum alloy. A very impressive 19 ksi fatigue strength at 10^7 cycles was obtained in the 2024Al-DSC material. The fatigue strength of A354-T6 alloy was determined to be about 10 ksi at 10^7 cycles.

The microstructure of the DSC material (as-received and following thermal treatment) was characterized by TEM. The aluminum matrix grains were found to contain a moderate density of dislocations. The nanoparticles were found to have the structure and composition of α-Al_2O_3. The particles are nano-sized (30–100 nm) in the as-synthesized material, but they coarsen to 100–1000 nm following high-temperature thermal treatment, independent of time or temperature. After the initial holding times, little or no change in the sizes of the particles occurred at longer times and independent of temperature. This points to great thermal stability of these materials and a high, nearly constant hardness as a function of time and temperature. The TEM results are consistent with the SEM observations reported previously.

Conclusions

Three different paths were adopted to develop and evaluate high-temperature aluminum alloys for turbocharger compressor wheels and housing applications. The versatility of the ThermoCalc software was demonstrated in the plotting of the phase diagrams. The Al-Y and Al-Yb binary-phase diagrams were generated and validated. The Al-Y-Yb ternary system will be modeled. Slight improvement in the tensile strength was realized only at test temperatures above 300ºC for the NASA 388-T5 alloy compared with the current materials. The degree of improvement was deemed to be insignificant compared with the further development needed for the new casting process and prototype trials. The decision was made to discontinue the evaluation work for the NASA 388-T5 alloy for turbocharger applications. The DSC material exhibited very impressive high-temperature tensile and fatigue strength. Excellent thermal stability was confirmed with SEM and TEM studies. The DSC material has high potential to be used to replace the current C355 alloy to achieve improved material strength and thermal stability. Other important material properties such as creep resistance, notch sensitivity, and machinability will be further evaluated.

Publication/Presentations

P. Prasad, Y-C. Chen, and V. K. Vasudevan, "Microstructure and Mechanical Properties of New, Cast Aluminum Alloys for High Temperature Diesel Engine Applications," in *Symposium of Challenges for High temperature Alloys in Aerospace, Land-based Gas Turbines, Power and Transportation Systems*, ASMI Fall Meeting, Columbus, OH, October 18–20, 2004.

P. Prasad, Y-C. Chen, and V. K. Vasudevan, "Characterization and Aging Studies of New, Cast Aluminum Alloys for High Temperature Diesel Engine Applications," in *General Abstracts Session on Mechanical Behavior and Characterization,* TMS/MST 2004 Fall Meeting, New Orleans, September 26–29, 2004.

P. Prasad, P. C. Becker, Y-C. Chen, and V. K. Vasudevan, "Microstructure of New, Cast Aluminum Alloys for High Temperature Diesel Engine Applications," in *General Abstracts Session on High Temperature Alloys,* TMS/MST 2003 Fall Meeting, Chicago, November 7–11, 2003.