N. High-Temperature Aluminum Alloys

Yong-Ching Chen
Materials Engineering
Cummins, Inc.
1900 McKinley Ave.
Columbus, IN 47201-3005
(812) 377-8349; fax: (812) 377-7226; e-mail: yong-ching.c.chen@cummins.com

DOE Technology Development Area Specialist: James J. Eberhardt
(202) 586-9837; fax: (202) 586-1600; e-mail: james.eberhardt@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

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Objectives

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

Approach

- Develop ternary-phase compositions by means of modeling of the equilibrium-phase diagram, 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 possible by this method.
- Evaluate a nanophase particulate-reinforced aluminum alloy patented by Chesapeake Composites, Inc.

Accomplishments

- Predicted the binary phase diagrams of Al-Y and Al-Yb accurately and verified them using ThermoCalc.
- Found that the improvement in high-temperature strength of the NASA 388 alloy was not significant enough for further pursuing.
- Observed that the dispersion-strengthened composite (DSC) material exhibited significantly lower thermal conductivity and lower coefficient of thermal expansion than those of current production aluminum alloys.
- Found that the tensile strength of the DSC sample produced in 2005 was much lower than that of the billets tested in 2002. The inferior strength of the current DSC billets was most likely due to the presence of aluminum veins and defects inside the aluminum matrix. Improvement in quality is needed.
- Completed machinability studies of DSC material. Optimal operation parameters for cutting, turning, and milling were determined. The tool wear was minimal, similar to the machining of 6061-T6 aluminum.

Future Direction

- Use ThermoCalc to generate the Al-Y-Yb ternary system and identify optimal compositions for casting trial and material property characterization.

- Improve billet quality, and complete notch sensitivity and creep tests of DSC material.
- Use DSC material for rig testing machine turbocharger compressor wheel.

Introduction

The new emission requirement in internal combustion of diesel engines mandates that the turbocharger compressor be operated at significantly higher temperature and pressure. This condition makes standard castable aluminum alloys unusable as new-generation turbocharger material, 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 investigation of three different paths of providing strength retention in aluminum alloys at high temperatures. Path 1 uses a ternary-phase aluminum alloy utilizing 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 is performed to determine if additional rare earth (or other metal) elements produce beneficial properties at a reasonable cost. The main goal of this path is to generate the phase diagram of Al-Y-Yb, using ThermoCalc software. Because there are 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 it is preferred for Cummins to use alloy with lower silicon content. Eck Industries purchased the license for the NASA-developed technology on high-silicon casting alloy 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 Inc. The nanophase particulates at 50 vol % provide adequate high-temperature strength in early experiments; however, the particulate-loaded alloy could only be forged or squeeze cast so complex shape capability is limited. The mechanical behavior of this DSC material is being fully characterized. Casting modifications will be investigated to determine shape capability for the alloy.

Results

Path 1: Ternary-Phase Aluminum Alloy Development

In a previous report, the ternary-phase diagram of the Al-Fe-Mn was developed by using ThermoCalc software. The versatility of the ThermoCalc had been demonstrated. A binary Al-Y phase diagram was then generated by using the ThermoCalc, and it was validated against literature data. The work on thermodynamic assessment of Al-Yb binary by using ThermoCalc was also carried out. In general, it is in good agreement with the standard phase diagram published in the literature.

However, it is important to note that unlike most elements, the rare-earth elements yttrium and ytterbium are not widely used. For the ternary Al-Y-Yb system to be predicted, the minimum information needed is the assessment of Y-Yb system. Without any experimental data, it is not possible to know if such ternary predictions are accurate or not. So the minimum step we need is to get Y-Yb system; otherwise, one axis of our ternary diagram may not be correct. We need data in terms of the actual thermodynamics of the system, for example, heat of mixing and activity data. We have to estimate the actual Gibbs energy for the compounds and then make the fit to the polynomial terms. Much effort was focused on experimentally generating the Y-Yb binary phase diagram. This will allow us to predict the Al-Y-Yb ternary system.

Path 2: NASA 388-T5 Aluminum Alloy

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 to those of the current production materials. Slight improvement in the tensile strength was only realized at test temperatures above 300ºC for the NASA 388-T5 alloy as compared to the current materials. The degree of improvement was deemed to be insignificant as compared to 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 intended application.

The NASA 388-T5 alloy was originally developed for automotive engine components such as pistons to utilize less material, which can lead to reducing part weights, material cost, as well as improving gas mileage and engine durability. The potential application of the NASA 388-T5 alloy in diesel engine pistons was communicated to the piston suppliers. One of the piston suppliers conducted fatigue tests of the NASA 388-T5 alloy and their production aluminum alloy at 350ºC. The NASA 388-T5 alloy exhibited slightly better fatigue strength at 350ºC than the production aluminum alloy. However, the NASA 388-T5 alloy was found to be difficult to cast in diesel piston size without defects. The piston supplier also decided not to pursue the development of NASA 388-T5 alloy in the piston application.

Path 3: Particulate-Reinforced Alloy

This task involves a nanophase particulate-loaded aluminum alloy patented by Chesapeake Composites Inc. A patented, low-cost, liquid-metal infiltration process is utilized 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 (CTE) of metal matrix composites (MMCs). It was claimed that this composite can be readily turned using tungsten carbide (WC) tooling and drilled and tapped using high-speed steel tools. Potential applications include pistons, compressor wheel, and engine components.

Initial tensile and fatigue tests of 1090 Al and 2024 Al alloy reinforced with nano-scale Al_2O_3 particles at elevated temperatures showed impressive results. Almost 100% improvement in tensile strength and yield strength was obtained on the DSC material as compared to those of the current production materials. No degradation in the tensile strength and fatigue strength was observed in the DSC material after 500 h of thermal soaking at 400ºC.

1. <u>Microstructural Characterization</u>

Extensive microstructural characterization of 2024Al-DSC material has been carried out. Particular attention was focused on developing an understanding of microstructural development in a 2024Al-Al_2O_3 composite during heat treatment. Figure 1 shows the variation of microhardness as a function of aging time for 2024Al-Al_2O_3 composite aged at 130^{o}C and 190^{o}C. Generally speaking, the aging time at peak hardness for the unreinforced all 2024 alloys is about 10 h (Ref. 1). However, the composite material reaches peak hardness after only 1 h of aging, which confirms the accelerated aging phenomenon we have discussed previously. Overaging and drop in hardness were observable at 190°C. Solution treatment and water quench greatly improve the microhardness of the composite. This is particularly because the dislocation generation due to thermal expansion mismatch between aluminum matrix and Al_2O_3 reinforcement.

An accelerated aging phenomenon has been reported, which is attributed to the increase in dislocation density due to Al_2O_3 reinforcement. Transmission electron microscope (TEM) analysis of the aged samples revealed the presence of θ’ and S’ precipitates, which were generally quite stable at 130°C, but underwent some coarsening with a concomitant drop in hardness following aging at 190°C. The dislocation density in room-temperature tensile-tested samples was quite low, which was consistent with the low ductility at this temperature. On the other hand, the dislocation density in samples thermally soaked and tested at higher temperatures (500 and 700°F) was high. This is thought to be associated with the combined effect of ease of plastic deformation at high temperatures, coupled with differential thermal contraction of Al and Al_2O_3 on

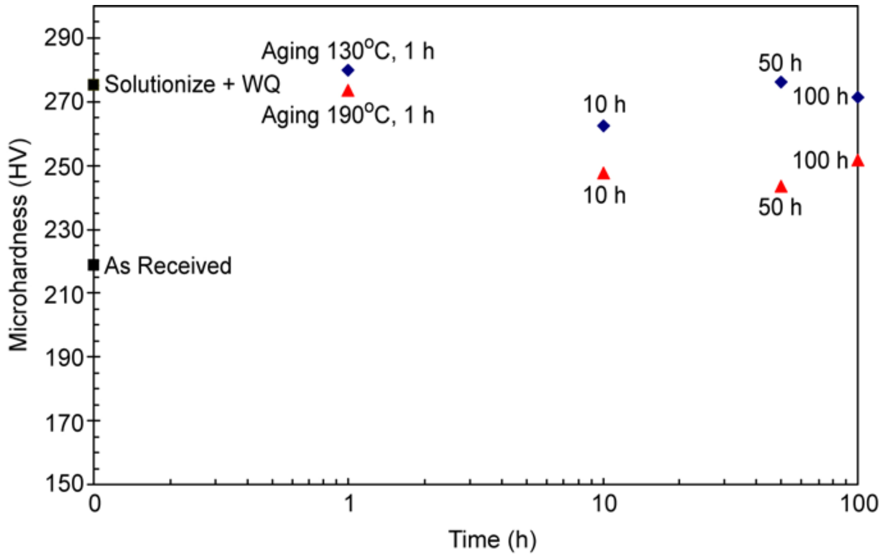

Figure 1. Variation of microhardness as a function of aging time for the 2024Al-Al2O3 composite.

cooling from the elevated temperatures of testing. Figure 2 shows TEM micrographs of the dislocation states of the 2024Al-Al_2O_3 as solutionized and water-quenched material.

2. Physical Properties

To further verify that the DSC material exhibits adequate mechanical strength to meet the operation requirements, mechanical and physical properties of DSC materials will be measured. Chesapeake Composites Corporations and PCC-AFT manufactured billets of DSC material with 1.7-in. diameter and 7.0 in. long. The DSC billets contain 40 vol % of Al_2O_3 nona-particles and were infiltrated with 1090 aluminum alloy.

Samples of a DSC material were machined for thermophysical property testing from room temperature to 400ºC. The density of the DSC material was measured to be 2.991 g/cm^3, which is about 12% heavier than that of the A354-T6 alloy (2.677 g/cm^3). The higher density needs to be taken into consideration during design because the

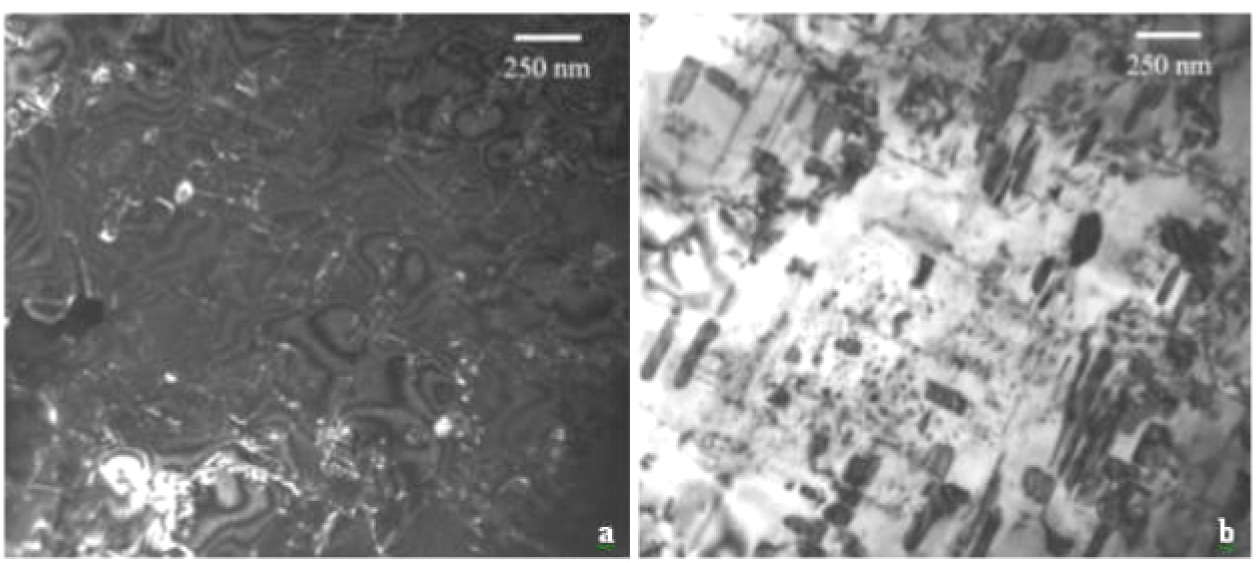

Figure 2. TEM micrographs showing the dislocation states of the 2024Al-Al_2O_3 as solutionized + water quenched material: (a) TEM DF (dark field) image; (b) TEM BF (bright field) image (precipitates).

compressor wheels made of DSC material will have higher reciprocal weight compared to those made of traditional aluminum alloy such as A354 alloy. Figure 3 displays the thermal conductivity of the DSC material as a function of temperature. Note that the thermal conductivity of the DSC material decreases as the temperature increases. This is most likely due to the presence of a high percentage of Al_2O_3 particles inside the aluminum matrix. The thermal conductivity of the DSC material was found to be much lower than that of a traditional aluminum alloy. The lower thermal conductivity in the DSC material may result in higher operating temperature. The mean CTE of the DSC material increases as the temperature increases, Figure 4. Note that the mean CTE of DSC material was significantly lower than that of a traditional aluminum alloy. The lower mean CTE was also most likely due to the presence of a high percentage of Al_2O_3 particles inside the aluminum matrix of the DSC material. The lower CTE in the DSC material may indicate smaller dimensional changes during operation.

3. Tensile Testing

Tensile samples with dimensions of 4.2-mm diameter by 18-mm gage length were prepared from the DSC billet for tensile testing at room temperature, 200ºC, 300ºC, and 400ºC without supplemental thermal soaking. Figure 5 shows the tensile strength of the DSC material as a function of temperature. The tensile strength of the DSC material tested in 2002 was also plotted for comparison. Note that the tensile strength of the DSC sample produced lately was much lower than that tested in 2002. The percent elongation and reduction of area at room temperature were almost zero. Some samples broke quickly before yielding such that no yield strength was available. The much lower tensile strength of the DSC samples manufactured in 2005 was unexpected.

4. Microstructural Characterization

To compare the microstructure of the current billets and that of the billets which exhibited much higher tensile strength, five tested tensile bars prepared from the DSC billets manufactured by Chesapeake Composites in 2002 were submitted for microstructure analysis to determine if defects were present in the material. The tensile bar samples were tested previously at varied temperatures and after a 500-h soak. Figure 6 shows the comparison between the tensile sample tested in 2002 and the billet samples manufactured in 2005. Note that the tensile sample tested in 2002 exhibited less cellular structure and much finer grain size as compared to the billet sample manufactured in 2005. Very few or no aluminum veins were observed in the tensile sample tested in 2002. The difference in the microstructure had resulted in significant difference in the tensile strength of the DSC billets.

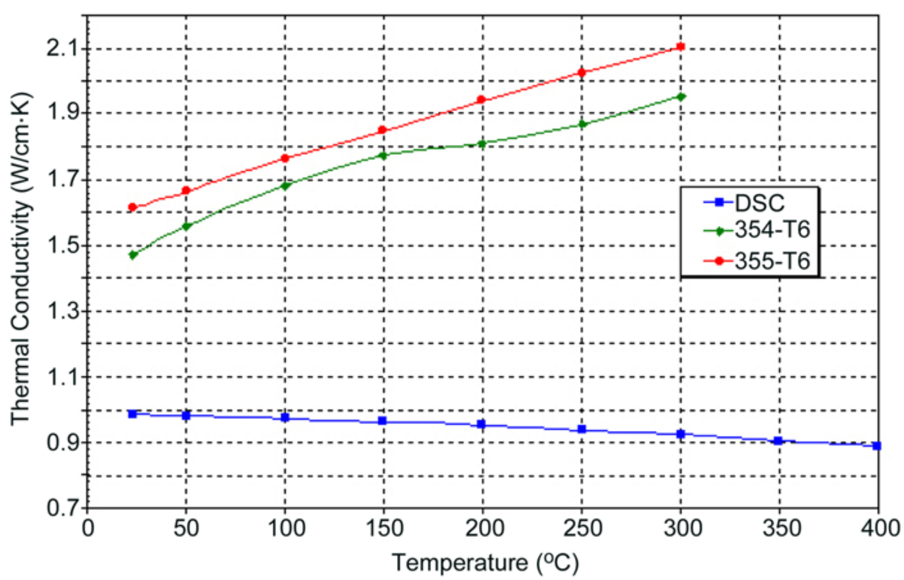

Figure 3. Thermal conductivity of the DSC material, 354-T6, and 355-T6 aluminum alloys.

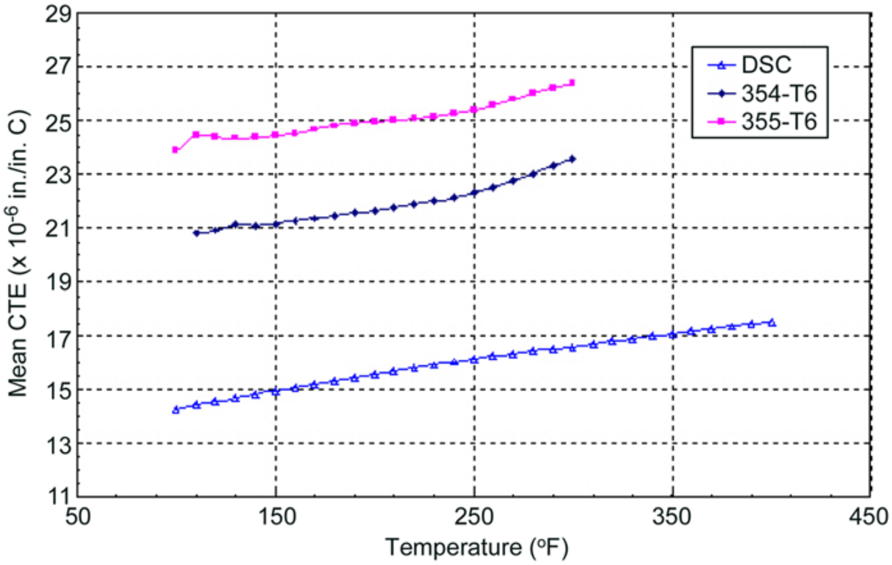

Figure 4. Mean CTE of the DSC material, 354-T6, and 355-T6.

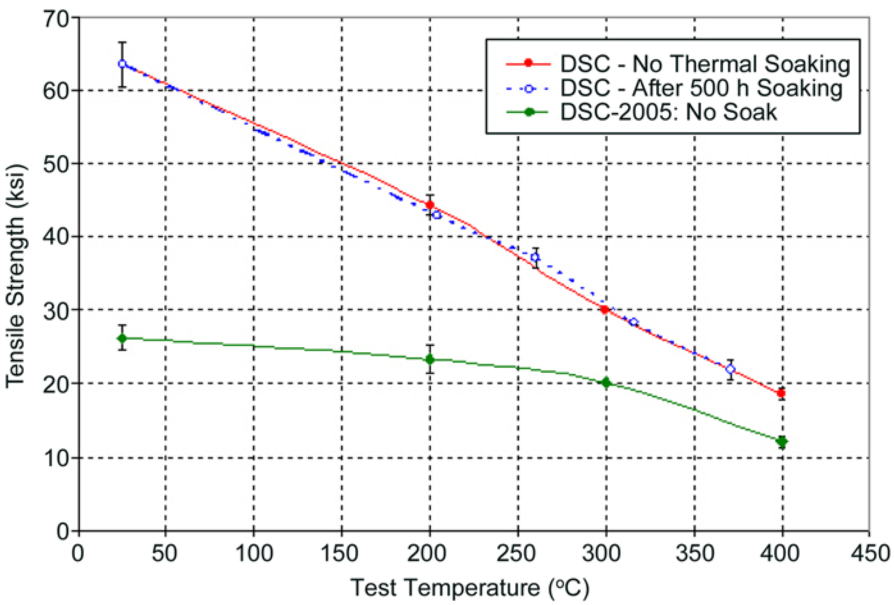

Figure 5. Elevated-temperature tensile strength of the DSC material manufactured in 2005 and DSC material manufactured in 2002.

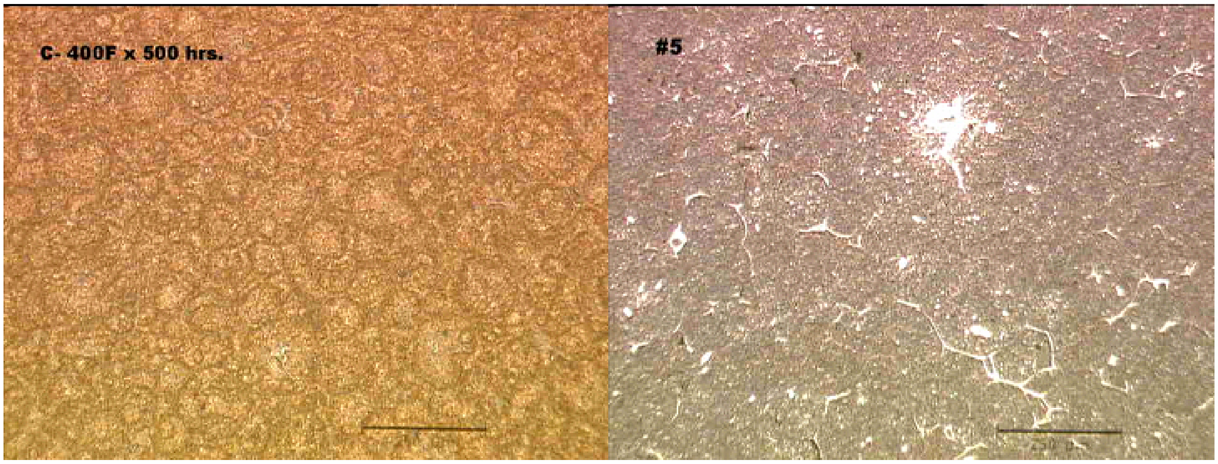

Figure 6. Comparison of the microstructure of tensile sample (left) to billet sample of different batch (right) at 100×. The microstructure of billet contains a larger number of large veins and defects.

According to the supplier, a different manufacturing process was used in making fine aluminum powders needed for making preforms. The difference in the quality of the powders had resulted in the dramatic difference in the final tensile strength. The quality of the current DSC billets was considered unsatisfactory, and further process development is needed by the supplier to get material close to past strength and quality.

5. <u>Machinability Study</u>

The machinability study of DSC aluminum was performed in the areas of drilling, sawing, single-point turning, and five-axis milling. The milling and drilling tools tested were selected by the Advanced Integrated Manufacturing Center, which consisted of carbide end mills from OSG Tooling and high-speed steel drills and taps.

A Daewoo Puma 240MS turret lathe, Figure 7(a), was used for the turning test. All turning parts were processed to machine the face then rough turn the outside to form two different diameters. All parts produced broken chips. There was no formation of long “springy” chips. Figure 7(b) shows excellent surface finish on both diameters. A Deckel Maho DMU50, Figure 8(a), was the five-axis machining center used for the test. The nonorthogonal fifth axis provides excellent machine stability. The part was 2-D roughed in 0.050-in. increments with the 0.375-in. two-flute end mill. The contour was finished utilizing all five axes of the machining center with the 0.250-in. ball end mill. The blade areas were finished, and the corners were removed

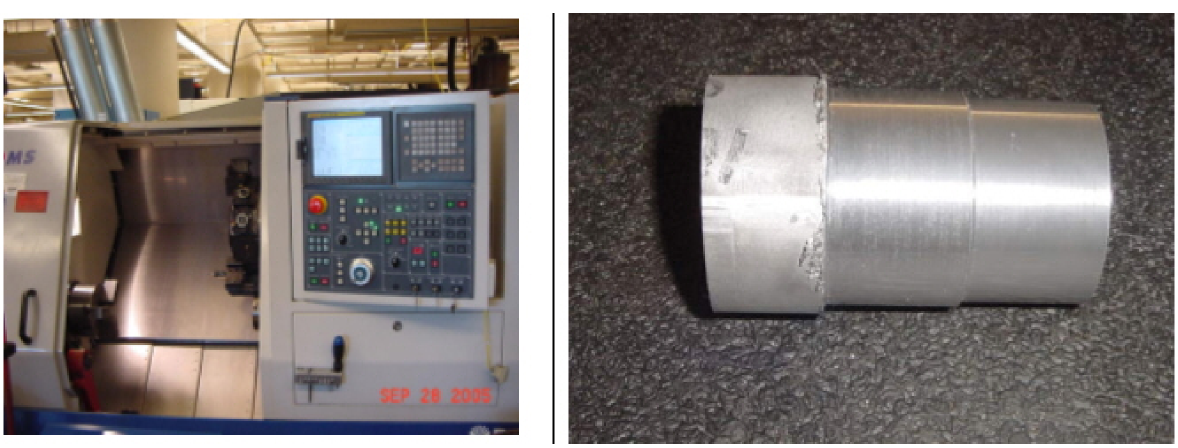

Figure 7. (a) A Daewoo Puma 240MS turret lathe was used for the turning test. (b) Excellent finish on both diameters was obtained with optimal cutting parameters.

Figure 8. (a) A Deckel Maho DMU50 was the five-axis machining center used for the milling test. (b) One demonstration part was completed by the five-axis machining center.

with the 0.125-6in. ball end mill. Figure 8(b) shows one demonstration part completed by the five-axis machining center. A microscope was used to measure the tool wear. The tool wear for the study was found to be minimal, similar to the machining of 6061-T6 aluminum. No significant difference in machining the DSC was noted when compared to the machining of traditional wrought aluminum alloys.

Conclusions

Three different paths are adopted to develop and evaluate high-temperature aluminum alloys for turbocharger compressor wheel 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 only realized at test temperatures above 300ºC for the NASA 388-T5 alloy as compared to the current materials. The degree of improvement was deemed to be insignificant as compared to 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. The DSC material exhibited very impressive high-temperature tensile and fatigue strength. Excellent thermal stability was confirmed with SEM and transmission electron microscope (TEM) studies. Physical property measurements of the DSC material were completed. The thermal conductivity of the DSC material was found to be much lower than that of a traditional aluminum alloy. The lower thermal conductivity in the DSC material may result in higher operating temperature. The mean CTE of DSC material was significantly lower than a traditional aluminum alloy. The lower CTE of the DSC material may indicate smaller dimensional changes during operation. The tensile strength of the DSC sample produced in 2005 was much lower than that of the billets tested in 2002. The inferior strength of the current DSC billets was most likely due to the presence of aluminum veins and defects inside the aluminum matrix. The quality of the current DSC billets is not satisfactory. Further process improvement is needed by the supplier. Machinability study of the DSC material was completed. No significant difference in machining the DSC was noted when compared to the machining of traditional wrought aluminum alloys.

References

1. R. J. Arsenault and R. M. Fisher, *Scripta Metall.*, **17**, 67 (1983).