

CAST ALUMINUM ALLOY FOR HIGH TEMPERATURE APPLICATIONS

Jonathan A. Lee

NASA-Marshall Space Flight Center, Mail Code ED33, Huntsville, AL 35812, USA

Abstract

Originally developed by NASA as high performance piston alloys to meet U.S. automotive legislation requiring low exhaust emission, the novel NASA alloys now offer dramatic increase in tensile strength for many other applications at elevated temperatures from 450°F (232°C) to about 750°F (400°C). It is an ideal low cost material for cast automotive components such as pistons, cylinder heads, cylinder liners, connecting rods, turbo chargers, impellers, actuators, brake calipers and rotors. It can be very economically produced from conventional permanent mold, sand casting or investment casting, with silicon content ranging from 6% to 18%. At high silicon levels, the alloy exhibits excellent dimensional stability, surface hardness and wear resistant properties.

Introduction

Technology Assessment

Aluminum-Silicon (Al-Si) alloys are most versatile materials, comprising 85% to 90% of the total aluminum cast parts produced for the automotive industry. Depending on the Si concentration in weight percent (wt.%), the Al-Si alloy systems fall into three major categories: hypoeutectic (<12% Si), eutectic (12-13% Si) and hypereutectic (14-25% Si). However, most Al-Si alloys are not suitable for high temperature applications because tensile and fatigue strengths are not as high as desired in the temperature range of 500°F - 700°F. In recent years, the development of diesel and direct fuel injection gasoline engines with high specific powers have resulted in a big performance impact on piston materials due to increased combustion pressures and piston temperatures.

Most of the Al-Si cast alloys to date are intended for applications at temperatures of no higher than about 450°F. Above this temperature, the alloy's microstructure strengthening mechanisms will become unstable, rapidly coarsen and dissolve resulting in an alloy having an undesirable microstructure for high temperature applications. Such an alloy has little practical application at elevated temperatures because the alloy lacks the coherency between the aluminum solid solution lattice and the precipitated strengthening particles [1-2]. In general, a large mismatch in lattice coherency contributes to an undesirable microstructure that cannot maintain excellent mechanical properties at elevated temperatures. Figure 1(A) is a diagram illustrating a coherent particle that has similar lattice parameters and crystal structure relationship with the surrounding aluminum matrix atoms. Figure (B) is a diagram illustrating a non-coherent particle having no crystal structural relationship with the aluminum atoms, which results in an alloy that has little or no practical application at elevated temperatures.

In order to enhance high strength, one approach is to use low cost particulate reinforcements to increase the strength of Al-Si alloys. This approach is known as the aluminum Metal Matrix Composites (MMC) technology [3-5]. It is noted that the strength for most particulate reinforced MMC's manufactured from an Al-Si matrix alloy are still inferior for high temperature applications because the alloy major strengthening phases are unstable for long term exposure at high temperatures. An alternative is the use of ceramic fibers reinforced MMC, which is an expensive process to produce for most automotive engine parts.

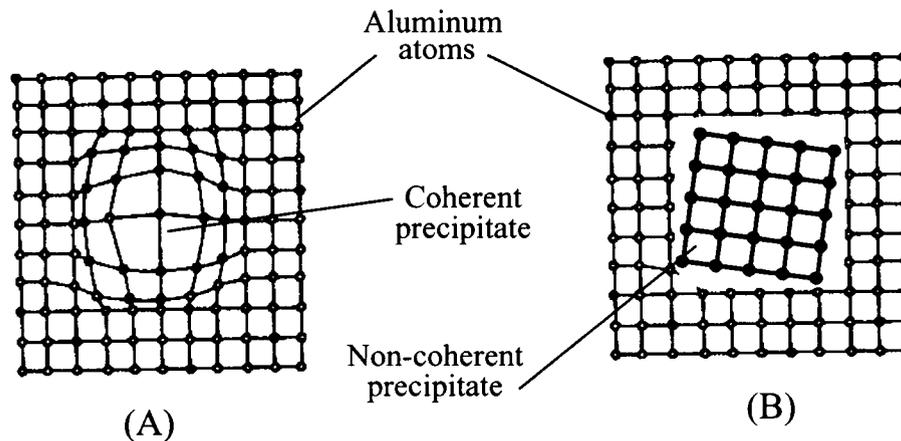


Figure 1: (A) illustrates a coherent precipitated particle that has similar crystal structure relationship with the surrounding aluminum matrix atoms. (B) illustrates a non-coherent precipitated particle.

NASA Aluminum Alloy Development

The newly developed NASA alloy is an ideal low cost aluminum alloy for high temperature cast components such as pistons, cylinder heads, cylinder liners, connecting rods, turbochargers, impellers, actuators, brake calipers and rotors. NASA 398 is an aluminum-silicon alloy that may be used in a bulk alloy form with silicon content ranging from 6% to 18%. At high silicon levels the alloy exhibits excellent dimensional stability, low thermal expansion, high surface hardness and wear resistant properties.

Due to increasingly stringent emission regulations for internal combustion engines, NASA 398 alloy is uniquely applicable for new piston design to reduce hydrocarbon emissions. Combustion analysis from engines has shown that the unburned fuel comes mostly from a ring-shaped crevice that is formed between the cylinder wall surface, the piston outside wall, and the top of the piston ring [6-8]. If the flame in the combustion chamber cannot travel deep into the piston's wall and enter the inside of the crevice, the unburned fuel is exhausted out of the combustion chamber in the expansion stroke as the main source of hydrocarbon emissions [9-10]. Current modification is to reduce the piston's crevice volume by moving the top piston ring closer to the top of the piston. Such piston modifications would require a stronger alloy to prevent the piston failure due to high mechanical and thermal loading of the top piston's ring groove and ring lands. NASA alloys have been applied for high performance diesel and direct fuel injection gasoline engines, with high specific power pistons requiring high fatigue strength in the pin boss area and high wear resistance of the flanks of the first ring groove.

Alloy Characteristics

Microstructures

NASA 398 is a hypereutectic alloy (16% w. Si), which has similar specifications for usage to conventional A390.0, Mahle 126, Zolloy Z16 and AE 425. It is a heat treatable Al-Si alloy consisting of small polygonal primary silicon particles evenly distributed in an aluminum matrix for high strength and high wear resistance applications at elevated temperatures. NASA alloys can also be made in eutectic and hypoeutectic forms (<13% wt. Si), which is similar to A384.0, A413.0, AE 413, Mahle 124, 356, 359, 360. NASA alloys can be produced economically from conventional permanent mold or sand casting, and they are best used for applications from 500°F (260°C) to about 750°F (400°C). Figure 2A and 2B show the typical microstructure of NASA alloys in hypereutectic and eutectic form, respectively.

In both types of NASA alloys, the silicon gives the alloy a high elastic modulus and low thermal coefficient of expansion. The addition of silicon is essential in order to improve the fluidity of the molten aluminum to enhance the castability of the Al-Si alloy. At high silicon levels the alloy exhibits excellent surface hardness and wear resistance properties. Strontium is used to modify the Al-Si eutectic phase, and phosphorus is used to modify the silicon primary particle size when the silicon concentration is greater than about 14 wt%. Both strontium and phosphorous are used today as a conventional grain refinement practice for all Al-Si alloys. Effective modification is achieved at a very low additional level, but the range of recovered strontium and phosphorus of 0.001 to 0.1 wt.% is commonly used.

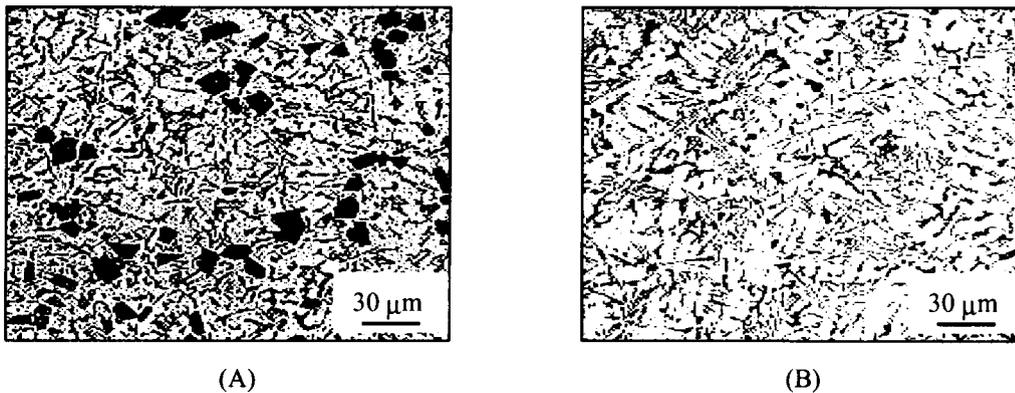


Figure 2: Microstructures of NASA alloys in hypereutectic (A) and eutectic (B).

To enhance the tensile strength at high temperatures, small amounts of transition elements are added to the Al-Si alloy to modify the lattice parameter of the aluminum matrix by forming compounds of the type Al_3X having $L1_2$ crystal structures. To maintain high degrees of strength at temperatures very near to their alloy melting point, both the aluminum solid solution matrix and the particles of Al_3X compounds are designed to have similar face-centered-cubic (FCC) crystal structure. They are also coherent because their lattice parameters and dimensions are closely matched. When substantial coherency for the lattice is obtained, these dispersion particles are highly stable, which results in high mechanical properties for the alloy during long exposures at elevated temperatures. The heat treatment is also slightly modified specifically to maximize the performance of the unique chemical compositions for NASA alloys.

The compounds of the type Al_3X particles also act as nuclei for grain size refinement upon the molten aluminum alloy being solidified from the casting process. They also function as dispersion strengthening agents, having the $L1_2$ lattice structure similar to the aluminum solid solution, in order to improve the high temperature mechanical properties.

Mechanical Properties

Figure 3 illustrates the dramatic improvement in the ultimate tensile strength (UTS) at elevated temperatures for a cast article produced from NASA alloys as compared with three well-known conventional alloy 332, 390 and 413 [11]. The UTS data is tested at 500°F, 600°F and 700°F, after exposure of all test specimens to a temperature of 500°F, 600°F and 700°F for 100 hours, respectively. It is noted that the tensile strength of NASA alloys, is more than three times that of those prepared from the conventional eutectic 413.0 alloy, and more than four times that of those prepared from hypo-eutectic 332.0 alloy and the hyper-eutectic 390.0 alloy, when tested at 700°F.

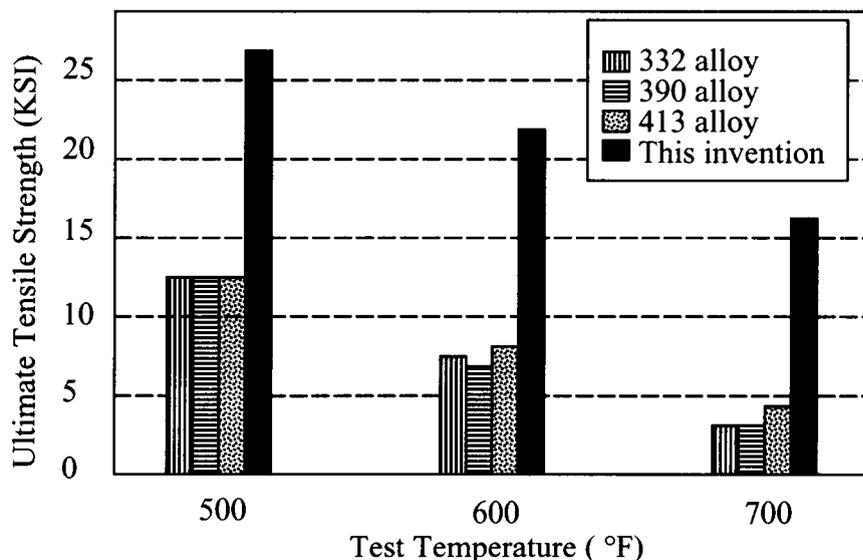


Figure 3: Comparison of tensile strengths at elevated temperatures for NASA alloys.

Thermal and Physical Properties

At room temperature, the density for the eutectic and hypereutectic alloys is not much different from most conventional Al-Si alloys, about 2.76 g/cm^3 (0.099 lb/in^3) for NASA 398, and 2.73 g/cm^3 (0.098 lb/in^3) for NASA 388. The modulus of elasticity is about 12.8 Msi (88.6 GPa), and a hardness value of 71 HRB (Rockwell B scale). Since NASA alloys are specifically designed for high temperature applications, the room temperature tensile and yield strengths are in the same range for most conventional 300-series cast aluminum alloys. The typical thermal properties as a function of temperature are given in Table I. The liquidus temperature is 619°C (1156°F) for NASA 398, and 581°C (1078°F) for NASA 388. The solidus temperature is 486°C (907°F) for NASA 398, and 483°C (901°F) for NASA 388. The solidification temperature range is 619°C - 486°C for NASA 398, and 581°C - 483°C for NASA 388, respectively.

TABLE I Typical Thermal and Physical Properties for NASA 398 alloy.

Temperature		Thermal expansion (a)	Thermal diffusivity	Specific heat	Thermal conductivity	Density
°F	°C	(10^{-6} .K)	(cm^2/sec)	(J/kg.K)	(W/m.K)	(g/cm^3)
72	25	18.50	0.525	820	120.0	2.76
212	100	18.65	0.519	874	125.4	...
392	200	19.17	0.506	915	128.0	...
572	300	19.72	0.489	952	129.0	...
662	350	19.93	0.480	990	131.4	...

(a) Thermal expansion coefficients given for hypereutectic alloy (16% Si).

Heat Treatment and Processing Cost

For a high temperature application of greater 600°F, a low cost heat treatment process similar to the T5 treatment is recommended. This unique heat treatment schedule complements the unique alloy composition to form a maximum amount of precipitates with uniform distribution and optimum particle size. Thus, NASA alloys have high temperature strength properties that are superior to the prior art alloys because of a unique combination of chemical composition and heat treatment processing. Implementation of NASA 398 could actually be cheaper than some conventional alloys and cost saving can be realized if a specific component's heat treatment can be switched to T5 from previous specifications of either T6 or T7, when appropriate. However, T7 and T6 heat treatments are recommended for NASA alloys when the maximum operating temperature is less than 550°F.

Initial production and casting trials have shown that NASA alloys can be cast and processed at a mass production value that is comparable with most conventional 300-series aluminum (<\$0.90/lb). NASA alloys can be cast using conventional gravity casting in the temperature range of about 1325°F to 1450°F, without the aid of external pressure. However, further improvement of tensile strengths will be obtained when NASA alloys can be processed with external pressure such as squeeze casting. NASA alloys are best used for applications from 450°F (232°C) to about 750°F (400°C). For instance, strength improvement for NASA 398 can be as much as 3 to 4 times higher than conventional cast aluminum alloys when tested at 600°F (315°C), after soaking the alloy at 600°F for 100 hours.

Potential Applications

Table II shows a guideline for material selection and potential applications of NASA alloys to meet substantially higher elevated temperature strength requirements than other conventional casting aluminum alloys. NASA alloys may be used in bulk alloy forms as hypoeutectic (6% – 9% Si), eutectic (10% - 13% Si) or hypereutectic (16% - 18% Si). It is an ideal low cost material for cast automotive components such as pistons, cylinder heads, cylinder liners, connecting rods, turbo chargers, impellers, actuators and brake calipers. At high silicon levels, the alloy exhibits excellent dimensional stability, surface hardness and wear resistant properties.

Table II Guideline for material selection and applications of NASA alloys.

NASA alloys	Potential Replacement	Applications
MSFC 398 (16% - 18% Si)	390, Zollner 16 Mahle 126 AE 425	<ul style="list-style-type: none"> • Pistons • Bearings • Cylinder liners • Brake calipers
MSFC 388 (10% - 13% Si)	383, 384 413, Mahle 124 Thermotur	<ul style="list-style-type: none"> • Cylinder blocks • Cylinder heads • Connecting rods • Pistons
MSFC 358 (6% - 9% Si)	356, 357 359, 360 201, 206, 224, 242	<ul style="list-style-type: none"> • Jet engine parts • Turbochargers • Metal composites • Impellers

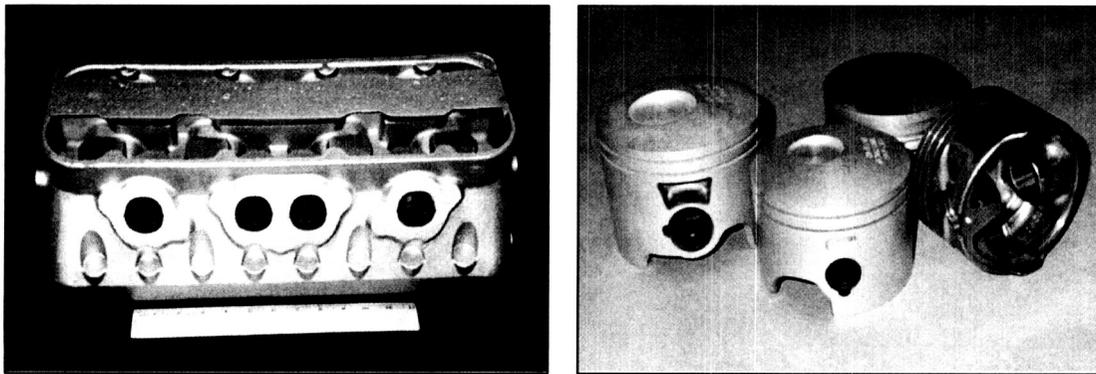


Figure 4: Full-scale cylinder head and pistons produced from sand and permanent mold casting.

Figure 4 shows the full-scale cylinder head and pistons produced using NASA alloys from conventional sand casting and permanent mold casting processes. NASA alloys can be cast and processed at a mass production value that is comparable with most conventional 300-series aluminum. NASA alloys may also be used as alloy matrices for the making of aluminum metal matrix composites (MMC), which comprise a filler material in the form of particles, whiskers, chopped fibers and continuous fibers. The filler materials in the composite should not be confused with the strengthening particles Al_3X . The filler or reinforcement materials added into the aluminum MMC usually have minimum dimensions typically in the range of 1 to 20 microns. Suitable reinforcement materials for making aluminum MMC include common materials such as silicon-carbide (SiC) and aluminum-oxide (Al_2O_3). These reinforcements are present in volume fractions up to about 60% by volume. In stir-casting technique for composites, the approach involves mechanical mixing and stirring of the filler material into a molten metal bath. The temperature is usually maintained below the liquidus temperature to keep the aluminum alloy in a semi-solid condition in order to enhance the mixing uniformity of the filler material.

Conclusion

Originally developed as piston material to meet U.S. automotive legislation requiring low exhaust emission, the novel NASA alloys also offer dramatic increase in strength, enabling components to utilize less material, which can lead to reducing part weight and cost as well as improving gas mileage and performance for auto engines. In hypereutectic form, the alloys also have greater wear resistant, surface hardness and dimensional stability compared to conventional cast aluminum alloys. NASA high strength alloys can be produced economically from conventional permanent mold, sand casting or investment casting, and they are best used for high temperature applications from 450°F (232°C) to 750°F (400°C).

References

1. Donald R. Askeland, *The Science and Engineering of Materials* (PWS-Kent Publishing Co., 2nd edition, Boston, 1989), 322
2. Leonard E. Samuels, *Metals Engineering: A Technical Guide* (ASM International, Metals Park, OH, 1988), 245-247.
3. R. Bowles, "Metal Matrix Composites Aid Piston Manufacture," *Manufacturing Engineering*, (5) 1987.
4. A. Shakesheff, "Elevated Temperature Performance of Particulate Reinforced Aluminum Alloys," *Materials Science Forum*, Vol. 217-222, pp. 1133-1138 (1996).
5. P. Rohatgi, "Cast Aluminum Matrix Composites for Automotive Applications," *Journal of Metals*, 4 (1991).
6. J. T. Wentworth, "The Piston Crevice Volume effect on Exhaust Hydrocarbon Emission," *Combustion Science & Technology*, 4 (1971), pp. 97-100.
7. T. Saika, "Effects of a Ring Crevice on Hydrocarbon Emission from Spark Ignition Engines," *Combustion Science & Technology*, 108, (1995), pp.279-295.
8. John B. Heywood, *Internal Combustion Engine Fundamental* (McGraw-Hill, Inc., NY, 1987.)
9. W. Haskell, "Exhaust HC Emissions from Gasoline Engines Surface Phenomenon," *Society for Automotive Engineering*, Paper #720255 (1972).
10. J. Wentworth, "Piston and Ring Variables Affect Exhaust Hydrocarbon emissions," *Society of Automotive Engineering*, Paper #680109 (1968).
11. J. Gilbert Kaufman, *Properties of Aluminum Alloys* (ASM International, Materials Park, OH, 1999).

**The 132nd TMS Annual Meeting & Exhibition
San Diego Convention Center, San Diego, CA
March 2-6, 2003**

Cast Aluminum Alloy for High Temperature Applications

Jonathan A. Lee

NASA/Marshall Space Flight Center (MSFC)
Materials, Processes & Manufacturing Department
Mail Code ED33
Huntsville, AL 35812 USA
Jonathan.A.Lee@nasa.gov

ABSTRACT

Originally developed by NASA as high performance piston alloys to meet U.S. automotive legislation requiring low exhaust emission, the novel NASA alloys now offer dramatic increase in tensile for many other applications at elevated temperatures from 450°F (232°C) to about 750°F (400°C). It is an ideal low cost material for cast automotive components such as pistons, cylinder heads, cylinder liners, connecting rods, turbo chargers, impellers, actuators, brake calipers and rotors. As a newly developed aluminum-silicon alloy, with silicon content ranging from 6% to 18%, it can be very economically produced from using conventional permanent mold or sand casting. At high silicon levels, the alloy exhibits excellent dimensional stability, surface hardness and wear resistant properties.