Materials Science & Engineering A 648 (2015) 401–411

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Factors influencing thermal conductivity and mechanical properties in 319 Al alloy cylinder heads

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ARTICLE INFO

Article history:
Received 10 August 2015
Received in revised form
20 September 2015
Accepted 22 September 2015
Available online 29 September 2015

Keywords:
319 Al cylinder heads
Cooling rate
Heat treatment
Microstructure
Mechanical properties
Thermal conductivity

ABSTRACT

Aluminium alloys have gained popularity for automotive applications, due to their high strength-to-weight ratio and thermal conductivity. In particular, cylinder heads are commonly produced from Al–Si–Cu alloys, given their age-hardenability and excellent castability. However, operating temperatures can induce thermal stresses in the heads, which can cause failure if the mechanical and thermal properties are insufficient. This research is a pioneering attempt at presenting several relationships between microstructure, mechanical properties, and thermal conductivity via the characterization of commercial 319 Al alloy cylinder heads. Optical microscopy, SEM-EDX, XRD, porosity measurements, tensile testing, Rockwell hardness testing, and thermal conductivity measurements using the transient plane source method were conducted at several critical head locations after thermal sand reclamation (TSR) and T7 heat treatments. The higher cooling rate at the bottom of the castings led to a finer dendritic structure, smaller intermetallic compounds, lower aspect ratio eutectic Si particles, and less porosity. Also, the T7 treatment promoted the formation of fine Al_2Cu precipitates distributed throughout the matrix and the coarsening and spheroidization of eutectic Si particles. Improvements in yield strength, tensile strength, and hardness were attributed to both grain boundary and precipitation strengthening, whereas improvements in thermal conductivity were attributed to solute depletion during aging.

1. Introduction

Increased fuel costs and government legislation on emissions have pushed automobile manufacturers to produce lighter and more fuel-efficient vehicles. Reducing the vehicle weight by using parts made of light alloys results in a significant decrease in fuel consumption, leading to a reduction of greenhouse and harmful exhaust gas emissions (CO_2, CO, NO_x, SO_x). As a result, Al alloys are a suitable replacement to ferrous alloys for automotive components, since they are two-thirds lighter and have a higher strength-to-weight ratio. In particular, 319 type (hypoeutectic Al–Si–Cu) alloys are common in the manufacture of cylinder heads, since they possess good mechanical and thermal properties at ambient and service temperatures (~250 °C).

Cylinder heads cover the engine cylinders and control the combustion process by conveying air and gasoline to the combustion chambers and exhausting hot combustion gases. Hence, they determine the engine's power output, fuel consumption, and exhaust gas emission behaviour. Yet, one of the cylinder head's largest concerns is the build-up of thermal stresses. Due to their complex geometry, the heat from combustion causes an uneven temperature field within the head, which leads to varying expansion rates in the part. The ensuing thermal stresses can reduce engine lifetime and cause part failure. As a result, the combustion temperature, and hence the engine efficiency, is limited by the maximum allowable thermal stresses in the material.

Much research has been conducted to improve the mechanical properties of aluminium alloys, including through alloying, enhanced cooling rates, and precipitation heat treatment. While doing so increases the alloy's resistance to thermal stresses, reducing the magnitude of these stresses can be just as important. One particularly promising avenue is improving thermal conductivity, which leads to a lower and more even temperature distribution in the part. Conductivity is directly related to the mobility of heat carriers: predominantly free electrons in ambient-temperature metals, but also lattice vibration waves (phonons) [1]. Lattice irregularities, such as impurities in solid solution, act as electron scattering centres that significantly reduce conductivity.

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http://dx.doi.org/10.1016/j.msea.2015.09.091

To a lesser degree, secondary phases also impede electron mobility, but their effects can be mitigated by promoting the formation of smaller, rounder, and uniformly-dispersed particles. Consequently, the thermal conductivity of Al–Si–Cu alloys can also be influenced by microstructural control, such as the use of chemical modification, varying cooling rate, and precipitation heat treatment.

First, Sr is typically used to chemically modify eutectic Si from a coarse acicular morphology to a fine fibrous structure. In addition to improving mechanical properties, increasing eutectic Si modification increases conductivity, since the fine fibres offer less resistance to the flow of electrons [2–7]. Second, increasing the cooling rate of a casting decreases secondary dendrite arm spacing (SDAS), which results in higher strength and reduced casting porosity. Faster cooling rates also promote the formation of finer and rounder eutectic Si particles and decrease the interdendritic eutectic pockets, both of which improve conductivity [2,3,6,8–10].

On the other hand, precipitation heat treatment can improve thermal conductivity, but the extent of which is strongly dependent on the solution heat treatment and aging times and temperatures. During the solution heat treatment, the dissolution of Cu-bearing phases reduces conductivity. However, this is offset by conductivity improvements that arise from the rapid fragmentation and spheroidization of eutectic Si particles at the solutionizing temperature. Then, with subsequent aging, fine and uniformly-distributed precipitates form and grow within the grains, which deplete the matrix of solute. Therefore, the greater amount of solute depletion in an alloy over-aged to the T7 condition than one peak-aged to the T6 condition results in higher conductivity in the former, although both show improvements relative to the as-cast condition [4,6,11–15].

There is a general understanding in the literature regarding the factors affecting thermal conductivity. Yet, there has been no comprehensive study in the published literature that examines the relationship between microstructure, mechanical properties, and thermal conductivity for varying cooling rates and heat treatments all within a single automotive component. As a result, this paper aims to provide such a study on commercial cylinder heads cast of an Al 319 type alloy. Cylinder heads are perfect candidates for this analysis, since they are integral components in the automotive industry that experience a variation in Si modification, cooling rate and heat treatment. In addition to providing a complete characterization of the heads, the findings will contribute to a greater understanding of the correlations between microstructure, mechanical properties, and thermal conductivity. This paper presents a baseline analysis in a long-term study to improve thermal conductivity in Al alloy cylinder heads.

2. Experimental procedure

The cylinder heads examined in this study were cast of a 319 type Al alloy by the Nemak facility in Dickson, Tennessee (Table 1). The heads were designed to cover three cylinders of a V6 engine block, providing two intake valves and two exhaust valves to each combustion chamber (Fig. 1). They were produced by a semi-permanent mould casting process, which used a permanent H13 steel mould and sand cores to attain the complex part geometry. The deck face, where the cylinder head will be in contact with the engine block, is the bottom of the casting, with risers connected to the cam towers situated at the opposite side.

As-cast cylinder heads were initially subjected to a thermal sand reclamation (TSR) treatment at 500 °C for 5 h and then naturally cooled to remove the sand cores via dissolution of their chemical binder. Subsequently, the cylinder heads underwent a precipitation heat treatment to a T7 temper for enhanced strength and dimensional stability. This heat treatment involved solutionizing the heads at 500 °C for about 6.25 h, followed by quenching in 90 °C water. Finally, aging was carried out at 250 °C for 4.25 h.

Many locations on the cylinder heads were analysed in order to effectively represent the overall component microstructure, mechanical properties, and thermal conductivity. The most critical locations for thermal stresses in cylinder heads are at the valve bridges, especially at the deck face [16]. Therefore, the heads were characterized at the bridge between the two intake valves ("In–In bridge"), the bridge between the two exhaust valves ("Ex–Ex bridge"), and the bridge between two cylinders ("Cyl bridge") (Fig. 1). While the bridges between intake and exhaust valves were also of interest, the sample sizes from these locations were inadequate mechanical properties and thermal conductivity measurements. In addition, samples were taken from both the deck face ("Bottom") and near the cam towers ("Top") at each of the three bridge locations, to account for the inherent microstructural variation in the castings. As well, two cylinder heads were characterized at these six locations, one that was TSR-treated and another that was also T7-treated, such to determine the effect of heat treatment. Their average compositions can be seen in Table 1, as determined via optical emission spectrometry (OEM) on 12 samples per head (using at least three readings per sample).

Most analyses were conducted on the right cylinders of the heads, as depicted in Fig. 1. However, in order to establish microstructural homogeneity between the cylinders and improve statistical significance, the centre cylinders were also characterized at the same locations for composition, dendritic structure, Al–Si morphology, porosity, and thermal conductivity. Therefore, while most characterization utilized 12 samples (two bridge depths on three bridge locations from two differently-treated cylinder heads), many utilized 24 samples. Moreover, samples at the middle depth of the casting along the bridges were characterized in terms of dendritic structure to confirm the progression of microstructure from top to bottom.

After cutting the samples from the cylinder heads, they were prepared by successive polishing steps using SiC papers, Al_2O_3, diamond suspension, and colloidal SiO_2. Microstructural characterization was performed using optical microscopy (OM) for dendritic structure, Al–Si eutectic and porosity, and scanning electron microscopy (SEM) for intermetallic phases. Phase microanalysis was carried out using energy dispersive X-ray spectroscopy (EDX). Buehler OmniMet image analysis software was used to measure the volume fraction of Al_2Cu intermetallics (using 20–30 backscattered electron images at 200 × magnification per 12 samples), quantify the eutectic Si morphology (using thousands of particles over seven optical micrographs at 1000 × magnification per 24 samples), and to facilitate manual secondary dendrite arm spacing (SDAS) measurements (using the linear intercept method with a minimum of 20 readings over at least seven images at 50 ×

Table 1
Average composition of the studied Al 319 cylinder heads.

	Si	*Cu*	*Fe*	*Mn*	*Mg*	*Zn*	*Ti*	*Ni*	*Cr*	*Pb*	*Sr*	*Al*
TSR	7.57	3.20	0.71	0.40	0.40	0.66	0.05	0.12	0.04	0.05	0.013	Bal.
T7	7.64	3.20	0.64	0.36	0.40	0.70	0.07	0.06	0.04	0.03	0.012	Bal.