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Characterization of the AC2A Cylinder Head and Development of Its Heat Treatment Process

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The cylinder head for a passenger vehicle made from the AC2A aluminum alloy was evaluated to determine its microstructure evolution during the solidification process and the corresponding thermal characteristics including fraction solid and non-equilibrium liquidus/solidus temperatures. Additionally, various heat treatment operations were evaluated in order to maximize the casting's High Cycle Fatigue (HCF) performance. It was determined that the Secondary Dendrite Arm Spacing (SDAS) was between 14-55μm and the estimated cylinder head solidification rate varied between 0.5 to 5.4ºC/s for thin and thick sections respectively. Hardness of the cylinder head in the heat treated condition varied between 47 to 70 HRB depending on the location. The critical valve bridge section had coarse SDAS of approximately 55μm and a slow solidification rate of approximately 0.5ºC/s that could contribute to localized segregation. An Fe/Mn ratio of 2:1 and a 40 ppm Sr addition was found to be optimum. The energy efficient heat treatment consisting of a two-step solution treatment at 505 and 525ºC for 1 and 2 hours and artificial aging at 220^{o}C for 2 hours resulted in the highest mechanical properties, i.e. UTS=278, YS=250 MPa and HCF=85 MPa. This modified heat treatment had an approximate 60% shorter process duration while exceeding the mechanical properties of the currently used temper. The application of interrupted quenching with a cooling rate of ~20ºC/s contributed to a reduction in quenching stress that could have an effect on improved fatigue performance.

Keywords: *AC2A aluminum cylinder head, heat treatment, thermal analysis, solidification rates, SDAS, mechanical properties.*

1. Introduction

Environmental concerns are driving vehicle manufacturers to achieve greater fuel economy and reduced greenhouse gas emissions. The powertrain is one area where significant improvements in energy utilization are achievable. For example, the diesel-based powertrain offers a significant improvement in energy efficiency on the order of 30% as compared to conventional gasoline engines. However, there are significant material challenges to be overcome. To obtain these high efficiencies, the diesel engine (particularly the cylinder head) must operate at higher temperatures and pressures, presenting a challenge for conventional Al based alloys [1-6]. A specific example is a critical cylinder section like the valve bridge being subjected to severe thermo mechanical fatigue that could disqualify conventional alloys. Current research is focused on the development of new alloy chemistries with improved high temperature performance and optimization of the existing 319 and 356 based chemistries together with the corresponding processing technology [1, 2, 6]. Improvements are needed in basic mechanical strength and ductility, creep, fatigue resistance and corrosion properties particularly when bio-fuels are used. If such properties can be produced using cost effective alloying additions and cost effective casting and heat treatment processes, this would represent a major achievement. Additionally, development of short cycle heat treatments integrated with the casting operation offer potentials for reduced manufacturing cycle time and for lowering the environment impact [9].

The objective of this paper is to determine the microstructure evolution during the cylinder head solidification process as well as to develop short heat treatment processing for the AC2A aluminum alloy with various chemistry modifications.

2. Experimental procedures

2.1. Alloy chemical composition and cylinder head testing methodology

Two variants of AC2A aluminum alloy chemistries containing 5.3%Si, 3.7%Cu, 0.14%Mg and 0.04%Ti were evaluated with an Fe/Mn ratio of 1:1 (0.56/0.56%) and 2:1 (0.56/0.28%) as well as with 40ppm Sr addition. The AC2A alloy is used for light duty cylinder heads cast using the semi-permanent process as presented in Fig. 1. A representative microstructure of the valve bridge section is presented in Fig. 2. Typically, this type of cylinder head is subjected to the heat treatment to improve its mechanical properties and ensure dimensional stability during in-service operation.

Test samples were extracted from cylinder head to determine the microstructure as well as hardness variation in thick as well thin casting's section. Casting critical section, i.e. valve-bridge was identified and evaluated. Cylinder head solidification rate was estimated between 0.5 to 5.4^{o}C/s for coarse as well thin sections respectively.

Laboratory melting and solidification experiments were conducted using the Universal Metallurgical Simulator and Analyzer (UMSA) Technology Platform [7]. Such physical simulations were carried out for the test samples extracted from cylinder head as well as AC2A ingots. This was done to determine sequence of alloy metallurgical reactions under the solidifications rates equivalent to various sections of the investigated cylinder head.

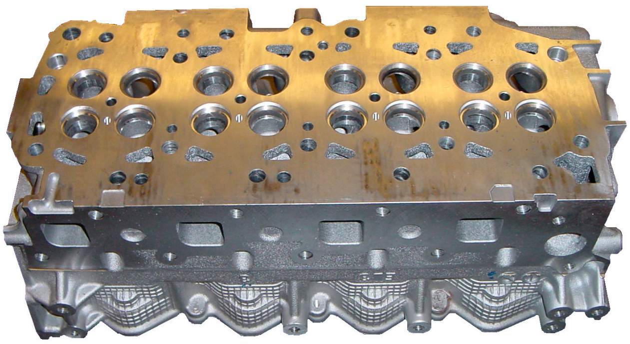

Fig. 1 Overall view of the cylinder head cast from the AC2A aluminum alloy using the semi-permanent process (riser side view).

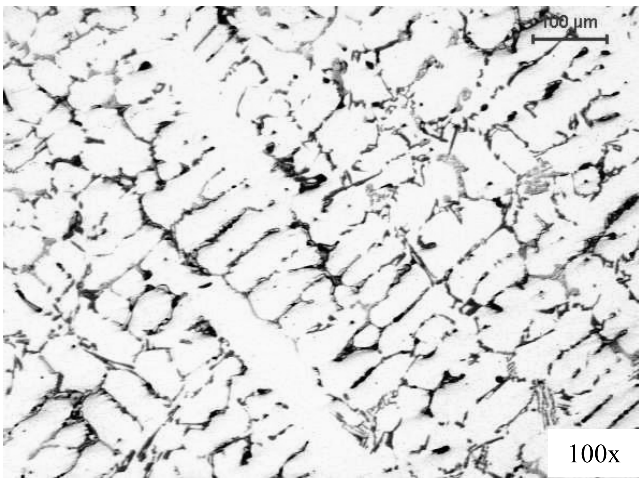

Fig. 2 Optical micrograph of the valve bridge section (100x).

Heat treatment optimization experiments were carried out for the test samples with a SDAS of 53.3±10.4µm that solidified at a cooling rate of approximately 0.5^{o}C/s. This selection of the as-cast structure ensured that the heat treatment optimization experiments were representative of the thickest cylinder head section, i.e., valve bridge. The duration of conventional heat treatment was approximately 16 hours. During heat treatment optimization studies the solution treatment temperatures were set at 495, 505 and 525°C and the solution time was chosen to be between 0.5 to 8 hours. One step as well as two step solution treatments were performed under the conditions as outlined in Table 1. Next the samples were subjected to artificial aging at 220°C for 2 hours followed by natural cooling to room temperature. The gas quenching process after completion of the solution treatment was performed directly to the artificial aging temperature (interrupted quenching) using compressed air (5 bars) as a quenching medium. The average quenching rate was ~20°C/s.

Table 1 Experimental variables (chemical composition/heat treatment parameters) and their effect on AC2A alloy mechanical and structural properties.

ID	Experimental Variables								Mech. Prop. and Structural Characteristics						
	Chemistry	Heat Treatment													
		Solution Treatment				Aging									
	Fe/Mn (wt%)	**Temp (°C)**	**Time (hrs)**	**2 step ST**	**IQ**	**Temp (°C)**	**Time (hrs)**	**Total Time (hrs)**	**UTS (MPa)**	**YS (MPa)**	**E (%)**	**Fatigue (MPa)**	**Hardness (HRB)**	**Porosity (%)**	**SDAS (µm)**
TP0	0.56/0.56	500 / 495	3 / 8	No	No	215 / 220	2 / 2	16*	239	215	0.9	68	60	11	39
TP1	0.56/0.56	495	8	No	No	220	2	12*	254	250	0.6	70	64	9	47
TP2	0.56/0.28	495	8	No	No	220	2	12*	274	250	0.8	78	67	2.7	47
TP3	0.56/0.28	505 525	1 2	Yes	Yes	220	2	6.5*	278	250	1	85	68	1.2	45

** - Includes heating time to solution/aging operations; IQ – interrupted quenching*

Mechanical properties evaluation including room temperature tensile testing, fatigue (rotating bending) as well as hardness (Rockwell tester in B scale under a 100kg load) was conducted to evaluate the effect of AC2A alloy chemistry and heat treatment conditions. Laboratory test bars were cast using a taper steel mold preheated to 200°C. Alloy melting and casting was done using standard foundry practices.

3. Results and discussion

3.1. Cylinder head microstructure and corresponding thermal characteristics

The investigated AC2A alloy cylinder head (Fig. 1) microstructure consisted of α Al dendrites, Al-Si eutectic and Cu, Mg based phases located within the interdendritic spaces (Fig. 2). The addition of 40ppm strontium had a minor effect on Al-Si eutectic modification, but could help to distribute localized porosity, particularly for slowly solidified casting sections (~0.5°C/s) typically observed in complex shape components. Fe based phases were up to 300µm long and had a Chinese Script morphology typical for a secondary alloy with Fe level of approximately 0.56% and Fe/Mn ratios of 2:1 and 1:1.

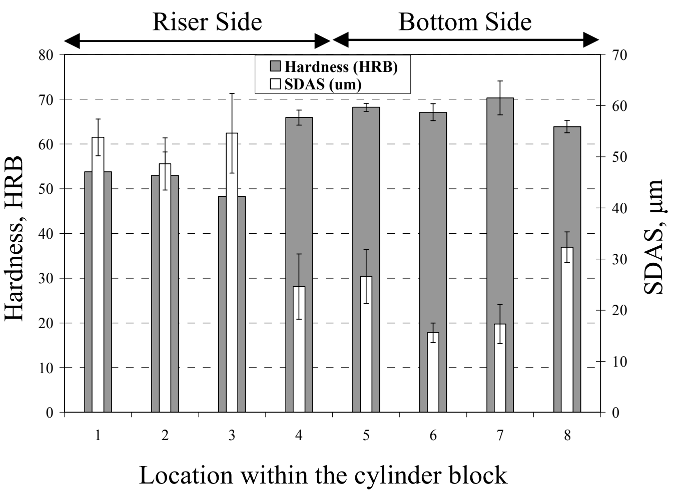

Fig. 3. Hardness (HRB) and Secondary Dendrite Arm Spacing (SDAS) vs. locations taken from the riser and the bottom side of the AC2A cylinder head. Note #3 is the valve bridge section.

The cylinder head SDAS varied between 14 to 55µm depending on the thickness of casting sections and the corresponding localized solidification rates as well as the location of the riser. The cylinder head

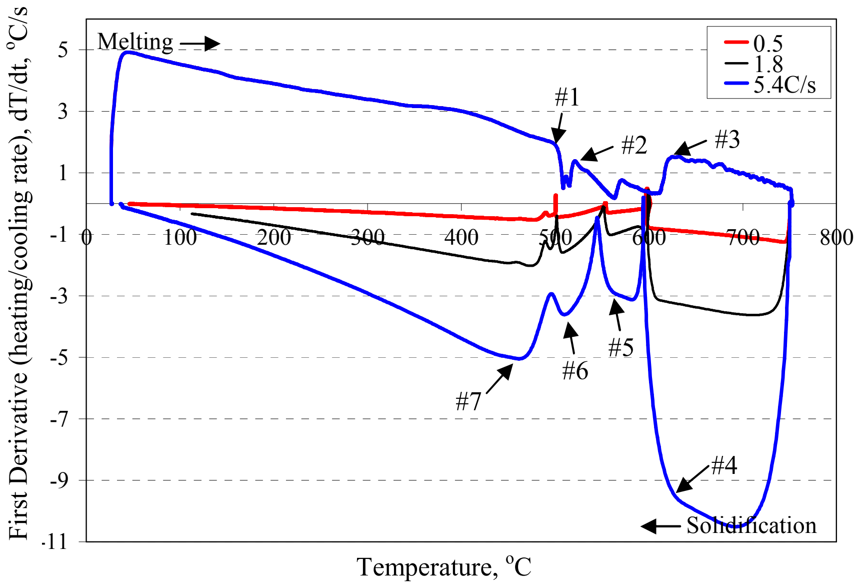

Fig. 4 First Derivative vs. Temperature melting and cooling curves from laboratory test samples solidified with cooling rates corresponding to various sections of the AC2A cylinder head. Phase transformations are pointed out by arrows (#1-7).

hardness in the heat treated condition varied from 49 to 70 HRB for thick and thin sections respectively. Fig. 3 presents the variation in the hardness and SDAS for various sections of the investigated cylinder head with respect to riser location. Higher hardness was achieved for thin casting sections with SDAS of approximately 20µm. Most likely, this was due to the accelerated dissolution kinetic of Cu, Mg phases during the solution treatment operation caused by reduced diffusion distances for thin casting sections with small SDAS. This type of microstructure and variation in mechanical properties could affect residual stress development particularly during subsequent casting heat treatment processing.

Cylinder head solidification rates were estimated based on the melting and solidification experiments carried out in the laboratory environment. Representative first derivative vs. temperature melting and cooling curves are presented in Fig. 4. Solidification rates during laboratory experiments were adjusted to achieve a microstructure with a SDAS size typically observed in various sections of the cylinder head. Phase transformations during AC2A alloy melting and solidification cycles are pointed out by the numbered arrows in Fig. 4. It was found that the AC2A alloy liquidus temperature (#4) shifted from approximately 600 to 620°C and the solidus (#7) was lowered from 500°C to approximately 446°C while increasing the solidification rate from 0.5 to 5.4°C/s. This resulted in an extended solidification range from 145 to 158°C. Analysis of the fraction solid vs. temperature curves indicated that a higher solidification rate (5.4°C/s) resulted in a lower fraction solid content at the Al-Si eutectic temperature that would have an effect on alloy feeding characteristics (Fig. 5). This detailed determination of the actual cylinder head solidification rates is required to provide accurate thermal alloy characteristics (liquidus temperature, fraction solid, etc.) for advanced solidification modeling studies [8].

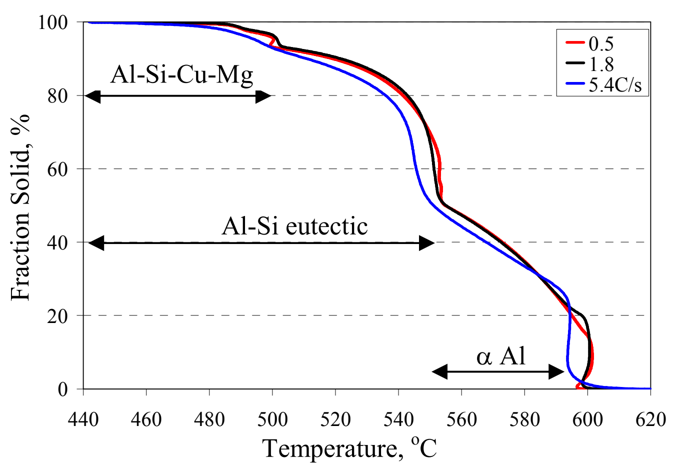

Fig. 5 Fraction solid vs. Temperature curves from laboratory test samples solidified with cooling rates corresponding to various sections of the AC2A cylinder head (i.e., 0.5, 1.8 and 5.4°C/s).

The Fe/Mn ratio of 2:1 and 40ppm Sr addition to the AC2A base alloy resulted in the lowest porosity and highest mechanical properties in the heat treated condition (see TP3 in Table 1). An increased concentration of Mn up to 0.56% could result in a large volume of FeMn based Chinese Script that could be particularly detrimental in slowly solidified casting sections. The highest average porosity, i.e., 11 and 9% was found for the AC2A alloy with an Fe/Mn rate of 1:1 (see TP0 and TP1 in Table 1).

Heat treatment parameters, alloy chemistry and corresponding structural and mechanical properties are presented in Table 1 while schematic temperature vs. time profiles for selected tempers are presented in Fig. 6. It was observed that for the TP3 condition (two-step solution treatment at 505°C for 1hr and 525°C for 2 hours followed by interrupted quenching and AA at 220°C for 2 hours) the highest hardness of 68 HRB was achieved. This value was approximately 13% higher compared with the TP0 industrial heat treatment conditions (60 HRB). Process duration of the TP3 compared to TP0 was 2.5 times longer, i.e., 16 hours vs. 6.5 hours. Mechanical strength, i.e., UTS/YS was increased from 239/215 MPa (TP0-Conventional heat treatment) to 278/250 MPa (TP3-Modified heat treatment). This gain in strength was achieved for an approximate 60% reduction in process time. Corresponding elongation was found to be similar for both analyzed tempers, i.e., 1% that represents a typical value for these types of castings.

Utilization of a two step solution treatment with the 1st step at 505°C for rapid dissolution of Cu and Mg based phases and the 2nd step at 525°C resulted in accelerated dissolution of Mg based phases and thermal modification of the Al-Si eutectic. The low melting point eutectics (i.e. Al_2Cu) were decomposed through dissolution instead of melting that could cause incipient melting and consequently significant loss of casting mechanical properties. The exact determination of the alloy's melting temperature (i.e. 505°C) was based on the thermal analysis heating curve as presented in Fig. 4, point #1. This approach maximized the effectiveness of the TP3 temper and led to a consequent process time reduction allowing for simultaneous improvement and control of both casting properties and heat treatment process productivity and associated costs.

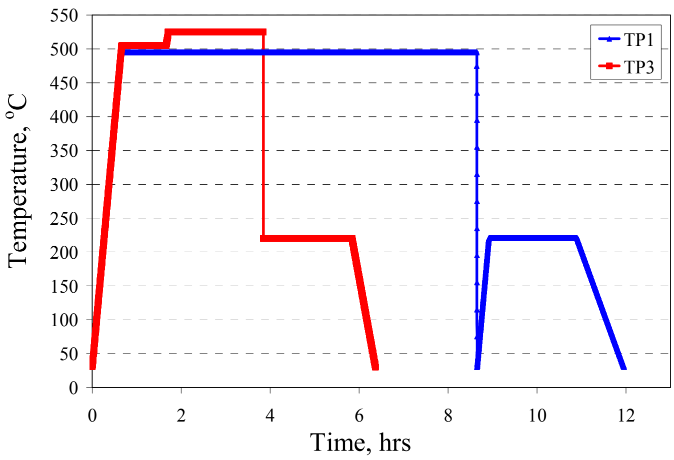

Fig. 6 Temperature vs. Time plots recorded during heat treatment experiments under the following conditions:
TP1 - Solution treatment at 495±0.5°C for 8hrs followed by artificial aging at 220±0.5°C for 2hrs.
TP3 - Solution treatment at 505±0.5°C for 1hr and 525±0.5°C for 2hrs followed by artificial aging at 220±0.5°C for 2hrs.

Rising energy costs should become a positive stimulus to revise the existing heat treatment standards. In the long term, these R&D activities will lead to the replacement of long heat treatment cycles currently used by industry and therefore, should enhance their energy efficiency. The expected benefits include less energy intensive processing with reduced impact on greenhouse gas emissions, as well as more efficient manufacturing allowing for wider application of light alloys and consequent component weight reduction.

4. Conclusions

Based on the presented metallurgical analysis carried out for the AC2A aluminum cylinder head as well as the laboratory casting and heat treatment experiments the following was concluded:

a) The investigated cylinder head had a solidification rate between 0.5 and 5.4°C/s for thin and thick sections respectively. The variation in solidification rate affected the following: i)

SDAS that varied between 14 to 55µm for the thick valve bridge and thin sections respectively, ii) hardness in the heat treated condition that varied between 49 to 70 HRB.

b) The Fe/Mn ratio of 2:1and 40ppm Sr addition to the AC2A base alloy resulted in the lowest porosity and in the highest mechanical properties in the heat treated condition.

c) The AC2A alloy liquidus temperature was shifted from 600°C to approximately 620°C and the solidus was lowered from approximately 500 to 446°C with an increasing solidification rate from 0.5 to 5.4°C/s. This resulted in an extended solidification range from 145 to 158°C.

d) Laboratory heat treatment experiments as well as industrial verification trials indicated that a modified temper (TP3) allowed for a process time reduction of 62% while improving the following mechanical properties: i) Hardness from 60 to 68 HRB, ii) UTS from 239 to 278 MPa, iii) YS from 215 to 250 MPa, iv) HCF from 68 to 85 MPa.

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