

Critical material issues in cast aluminium cylinder heads

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Abstract

Regulations calling for emission control and fuel savings and thus lightweighting of vehicles have increased the use of aluminium in the manufacture of vehicles. A major application of aluminium in the automotive industry is cylinder heads. In this application, the main advantage of aluminium, besides its lower density, is the excellent thermal conductivity, which allows the combustion heat to be extracted more rapidly. As a result of the permanent increase of combustion pressures and temperatures, material issues play a key role in the performance of aluminium cylinder heads. These material issues and their effect on performance are discussed in this paper.

Introduction

Aluminium alloys have almost completely replaced grey iron in cylinder head castings during the past 20 years thanks to their lower density and excellent thermal conductivity, which allows the combustion heat to be extracted more rapidly⁽¹⁾. Exposed to high-cycle fatigue (HCF) due to millions of combustion cycles and to low-cycle fatigue (LCF) resulting from thermal expansion and contraction during start-up and engine stop up to 10 times a day, cylinder heads are certainly a demanding application for aluminium alloys. Critical high-cycle fatigue (HCF) areas are on the water jacket side of the

flame-deck wall because of the prevailing cyclic tensile stresses, while the thin-walled valve bridge areas exposed to high temperatures may suffer cracking due to low-cycle fatigue (LCF). LCF resistance requires high temperature strength which in turn relies on alloy composition while the microstructure, porosity and surface quality are the key parameters for HCF life⁽²⁻¹¹⁾.

Any feature that promotes stress concentration and contributes to crack initiation or crack propagation is a major threat both to strength and ductility. Manufacturing practice takes every measure to reduce the quantity and size of such features in order to improve the overall quality of the casting. This paper reports the results of an extensive investigation of cylinder head castings taken from serial production and submitted to performance tests. The material issues critical for aluminium cylinder head castings are outlined.

Experimental

Cylinder heads were cast in Sr-modified EN1706 AlSi10Mg alloy (AC43100) which provides higher ductility than most secondary alloys thanks to its lower limits for impurity elements. A low pressure casting process was employed and made sophisticated and complex water-jacket designs possible with the application of sand cores. The solution heat treatment was performed in a drop-bottom furnace for five hours at 530°C. The heads were plunged into either water or polymer-water maintained at a minimum temperature of 75°C and 50°C, respectively. Artificial ageing was performed at 170°C for four hours. A total of forty generic cylinder heads were taken from serial production, were machined and assembled before they were submitted to the following performance tests.

Gasket thermal test cycle, designed to verify the cylinder head gasket, is one of the best test procedures for the engine cylinder heads. Test duration is 635 hours. The purpose of this dynamometer test is to investigate durability and reliability characteristics of static and dynamic sealing systems under extreme thermal conditions and the cylinder head. Test cycle is based on the cooling and heating of coolant and oil circulating in the engine externally. Coolant temperature varies between -20°C and 98±2°C as inlet and exit, respectively. Oil sump outlet temperature should be as high as possible (target 145°C).

Customer correlated general durability is the test to correlate the customer driving behaviour on the dyno engine. Test duration is 1202 hours and covers various aspects of engine running conditions. Test cycle includes certain number of full power and maximum engine rpm steps.

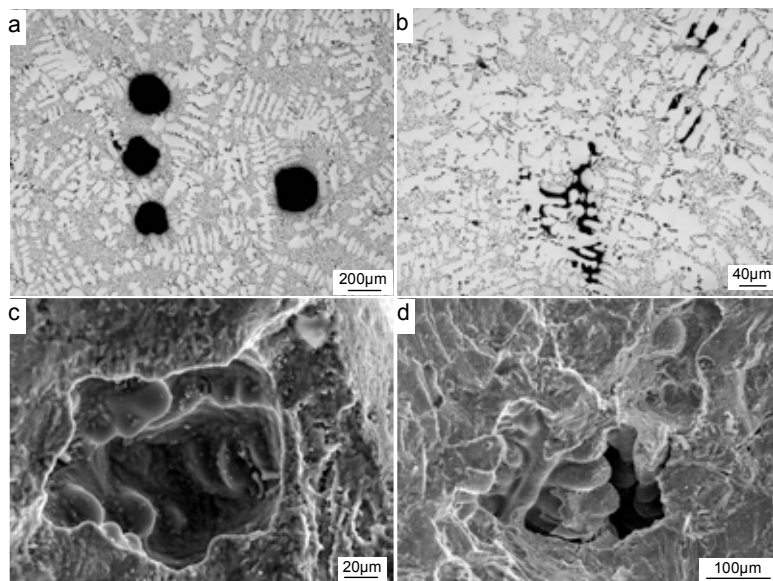


Fig. 1 Optical (a,b) and scanning electron (c,d) micrographs of gas (a,c) and shrinkage (b,d) porosity in cylinder head castings

The engine faces a major challenge at max power/torque for about 180 hours of the total test duration. Cyclic gas load is the the biggest contribution to the HCF. Engine coolant and oil are cooled internally by engine oil cooler and radiator.

High speed test lasts 825 hours and the engine runs mostly at high engine speeds together with the maximum power/load to the cylinder head. Cycling loading on the cylinder head is effective again for HCF under high engine rpms.

Maximum torque test is a 500 hour long test which forces piston cylinders under high cylinder peak fire pressure. Together with pistons, cylinder head is naturally tested with cyclic high peak fire pressure weakening the cylinder head for HCF's.

Forty cylinder heads from 10 different production campaigns over a period of 12 months were submitted to the performance tests described above. Non-destructive techniques were employed to find out about the presence and location of fatigue craks. These heads were subsequently sectioned. Small samples were removed from predetermined critical regions, adjacent to the water jacket side of the flame deck shown by finite element analysis to suffer the highest cyclic stresses. Those with fatigue cracks were further investigated with the common failure analysis techniques in order to identify the cause of cracking and were tested also for hardness, chemical composition and microstructural features. Standard metallographic practices were employed for the preparation of samples.

Results and Discussion

The chemical analysis, the tensile test results, and the hardness values are given in Tables 1 and 2, respectively. The quality index (Q.I.= UTS + 150 log (%elongation)) estimated from tensile test results were found to vary between 312 MPa and 487 MPa. Several of the head castings were found to contain fatigue cracks after the performance tests. The features which were found to have an impact on the performance of cylinder heads are discussed in the following section.

Porosity

Both gas and shrinkage porosity were encountered in aluminium cylinder head castings (fig. 1). The distribution was rather heterogeneous with many more pores located near the water jacket core where the solidification rate is relatively slower (fig. 2). Porosity has to be controlled to a minimum at critical locations of the head which are exposed to HCF, i.e. in the valve areas in the flame deck or the walls between flame deck and water jacket. Pores as small as 100 microns near the water jacket side of the flame deck were found to initiate cracks (fig. 3a). Those that did not take part in crack nucleation were often involved

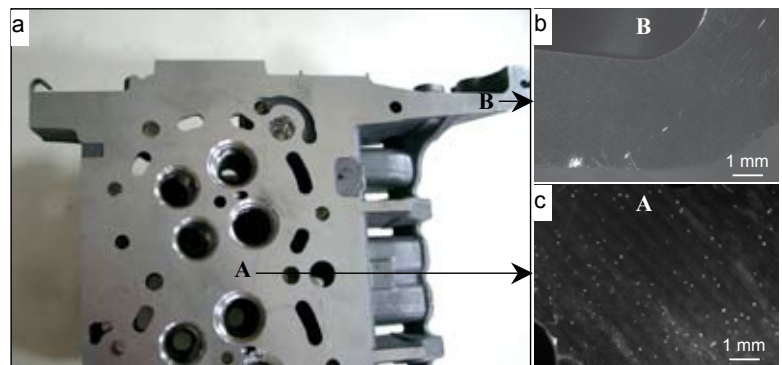


Fig. 2 (a) Distinction of porosity in cylinder head castings, (b) site B is nearly free of any porosity while (c) site A is crowded with pores

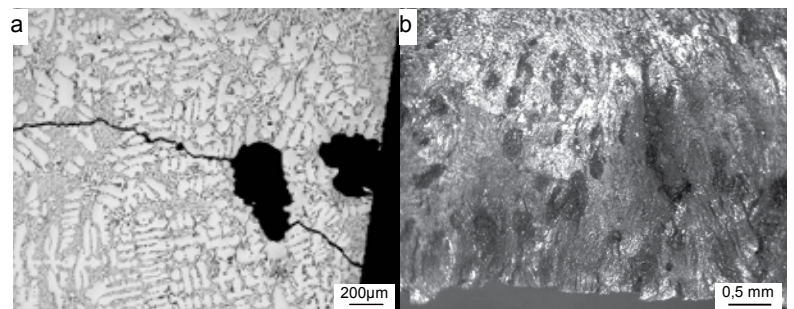


Fig. 3 (a) Pore which is involved in crack initiation near the water jacket side of the flame deck, (b) crack surface with a dense distribution of pores

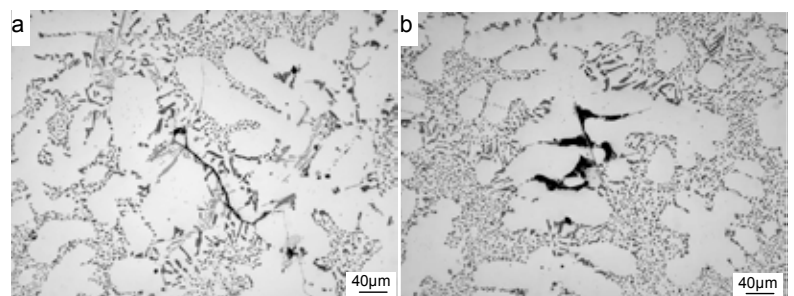


Fig. 4 AlFeSi intermetallic particles (a) which initiate a fatigue crack, (b) which block interdendritic melt flow and thus lead to porosity

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
min	9.40	0.092	0.018	0.010	0.241	0.004	0.131	0.009
max	10.33	0.182	0.077	0.023	0.409	0.026	0.183	0.032

Table 1. Chemical composition range of the cylinder heads investigated in the present work

	UTS, MPa	YS, MPa	Elongation, %	Hardness, HB
min	240	169	4	93.4
max	351	273	13	106.9
ave	329 ± 9	238 ± 12	9 ± 2	100 ± 9

Table 2. Tensile tests performed on specimens taken from the front face of the cylinder heads investigated in the present work

in crack propagation. The gas porosity was found to be reduced substantially when the density index during casting was kept below two. Gas porosity was a major quality problem, however, when the density index was allowed to exceed four. An exceptionally poor performance in one cylinder which has failed before the test was

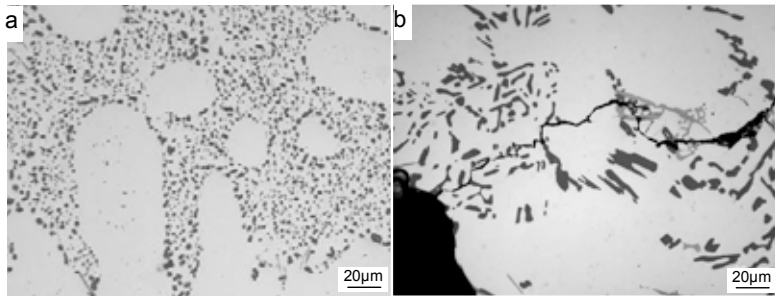


Fig. 5 (a) Silicon particles adequately modified and (b) silicon plates which have initiated fatigue cracking

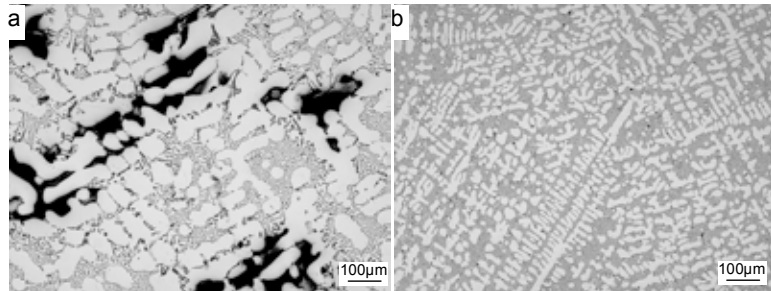


Fig. 6 Effect of solidification rate on microstructural features: local solidification time (a) 100s and (b) 10s

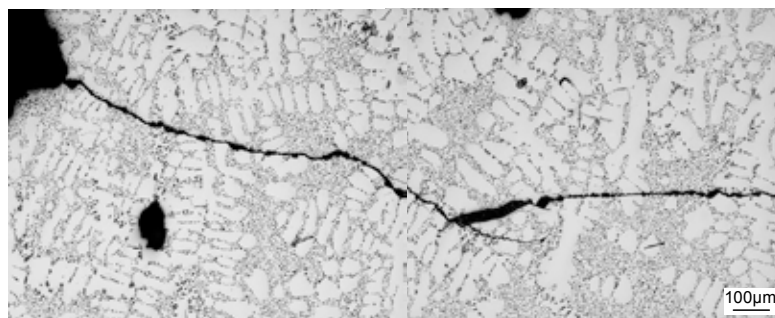


Fig. 7 A notch at a rough surface where a crack has initiated

over, was readily linked with extensive porosity dispersed across the section of the valve bridge area, once it was fractured after soaking in liquid nitrogen (fig. 3b). While both size and the number of shrinkage pores were smaller with respect to those originating from dissolved hydrogen, they were judged to be more detrimental due to their shapes. Shrinkage porosity was almost invariably interdendritic and was larger in size in heads with a coarser microstructure.

Intermetallic particles

The Fe content of the cylinder heads in the present work was controlled adequately and kept below 0.18 %wt. Nevertheless, the number as well as the size of the $\beta\text{-Al}_5\text{FeSi}$ platelets were found to increase with increasing Fe content even in this very narrow range. These particles were most frequent near the water jacket surface. This is basically due to the relatively lower rate solidification which prevail near the water jacket core. $\beta\text{-Al}_5\text{FeSi}$ platelets not only degrade the continuity of the aluminium matrix, act as stress raisers and, thus, aid crack initiation (fig. 4a), but also physically block the interdendritic melt flow, impair local feeding and thus led to microshrinkage porosity (fig. 4b). High rates of solidification are well established to favor the more compact cubic α phase which forms in chinese script morphology. Likewise, replacing some of the Fe with Mn produces a similar effect and promotes the transformation of the $\beta\text{-Al}_5\text{FeSi}$ platelets into α script which is less damaging to mechanical properties.

Modification of eutectic silicon

Sr, as much as 0.02 wt%, was found to alter the shape of the eutectic silicon phase from coarse, plates and needles to small, finely divided fibers (fig. 5a). In several heads, however, Si morphology was found to vary from fully modified, refined fibers to needles and platelets. While lower than required Sr addition was responsible for some of these cases, the poor Si morphology was almost always encountered near the water jacket side of the flame deck and was thus judged to result from slower solidification. These coarse broad brittle Si plates acted as stress raisers and provided planes of weakness that promoted both crack initiation and propagation (fig. 5b). Solution treatment employed in the present work was found to modify the eutectic Si further owing to high enough solution heat treatment temperatures to facilitate Si spheroidisation.

Solidification rate

Rapid solidification provides the greatest improvement in microstructural features and fatigue strength than any other means available to the foundryman. Rapid solidification does this by refining the microstructure and thus by dispersing shrinkage porosity, by reducing the extent of segregation and thus the size and volume fraction of intermetallic phases, by improving the modification of the eutectic Si. The rate of solidification is measured by the secondary dendrite arm spacing (SDAS) which thus serves as a significant quality parameter.

It is unfortunate, however, that the solidification is the slowest in those regions of the cylinder head which are exposed to HCF and are thus most critical. The SDAS measured in the water jacket side of the flame deck varies between 31 to 47 microns in the present work. There were no cracks in heads where the SDAS was below 35 microns while the frequency of fatigue cracks almost doubled when the SDAS was higher than 40 microns.

Two arbitrary parts were cast in AlSi10Mg alloy from two different pouring temperatures into a permanent mould merely to achieve different solidification rates by simply adjusting the superheat of the melt. The overall density of the parts cast from 730°C and 690°C were measured to be 2.607g/cm³ and 2.657g/cm³, respectively. This difference in density corresponds to a porosity difference of 2% by volume and is substantial. The microstructural features of the two parts are also strikingly different (fig. 6). The part cast with a higher superheat and which has thus solidified slowly shows a significant amount of shrinkage porosity while that cast with limited superheat and thus solidified very fast is perfectly sound. It is also worth noting that SDAS values of the slowly and rapidly solidified parts were approximately 60 and 20 microns, respectively. It is fair to conclude that achieving solidification rates which produces a SDAS value of 20 microns ensures a sound casting with no porosity. It is thus advisable to target a SDAS value as small as possible (preferably

below 30 microns) near the water jacket surface by enhancing the solidification rate in this otherwise, slowly cooling regions of the cylinder head.

Surface roughness

There were several cases where rough water jacket surfaces due to insufficient sand quality used in the manufacture of cores played a key role in crack initiation (fig. 7). This problem was fixed by using finer and higher quality sand. The flame deck surface quality is critical, not only because notches produced by unacceptable surface roughness serve as sites for fatigue crack initiation but also because flow conditions of the incoming gas are critical for the combustion process.

Residual stresses

Quenching from solution treatment leads to varying and sometimes extremely high residual stresses. Unless eliminated or reduced, these stresses can exceed, together with the stresses arising from operation, the fatigue endurance limit and finally lead to premature cracking in service. The highest residual stresses were found by experimental measurements to occur at typical crack locations implying that residual stresses played a key role in crack initiation and propagation.

Residual stresses measured at critical water jacket core regions in cylinder heads quenched in water, water-polymer and in air are shown in fig. 8. Residual stresses vary between 80-105 MPa in cylinder heads quenched in water (head #: 1, 4, 6, 9 and 18). Those measured in cylinder heads quenched in polymer-water (head #: 2, 11, 17, 22, 12 and 14) ranged between 15 and 55MPa. Finally, residual stresses measured in air-quenched cylinder heads were all lower than 15 MPa. It is clear from the foregoing that air-quenching practice gives the lowest residual stresses. With an average residual stress level (40 MPa) safely below the fatigue endurance limit of the present AlSi10Mg alloy (80 MPa) polymer-water quenching practice was adopted at the foundry since air quenching requires a rather high initial investment.

Conclusions

The cylinder heads which were cast with a sufficient level of eutectic silicon modification, with a limited amount of hydrogen and shrinkage porosity, with sufficiently high solidification rates to attain SDAS values below 35 microns, with Fe levels controlled under 0.12 wt%, with sufficient surface quality were never seen to fail in the performance tests. It is also worth noting that the likelihood of fatigue cracking was almost none in the cylinder heads which were quenched from the solution heat treatment in polymer-water so as to limit the residual stresses originating from

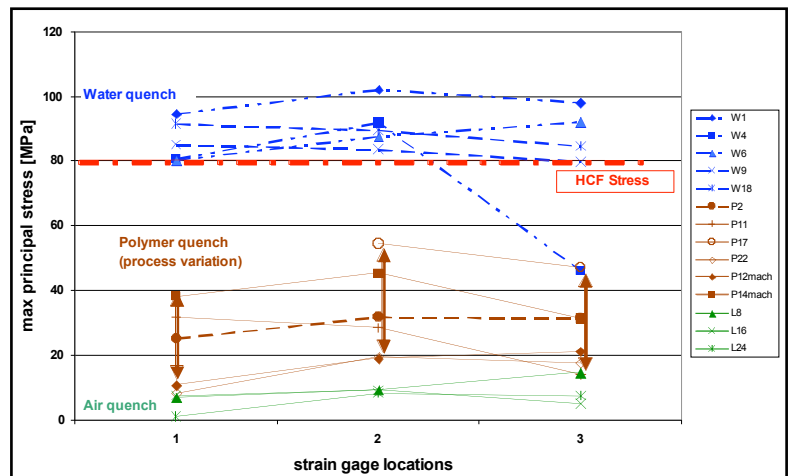


Fig. 8 Residual stresses measured in cylinder head castings

the quenching process.

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