

Tensile ductility improvement of AlSi9Cu1 alloy by chemical composition optimization

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Abstract: Diesel engines, characterized by higher breakout pressure and compression ratio in comparison with gasoline engines, require particularly elevated tensile properties for their engine parts. In order to maintain both high strength and high ductility in the cylinder head, i.e., to obtain higher percent elongation without further reducing the tensile strength, AlSi9Cu1 alloy was used to prepare the cylinder head in an aluminum diesel engine. At the same time, the effect of different modification elements, Na or Sr, and Fe content on the reduction of secondary dendrite arm spacing (SDAS) was discussed, and the design of T7 heat treatment parameters were analyzed in order to improve the tensile ductility. The result shows: (1) The SDAS is as small as $18\pm 3\ \mu\text{m}$ for the Sr modified alloy. (2) The percent elongation of the alloy with Sr modification increases by 66.7% and 42.9%, respectively, compared with the unmodified alloy and the alloy with Na modification. (3) Lower Fe content alloy (0.10%) gives good results in percent elongation compared to the alloy with higher Fe content (0.27%); in particular, after Sr modification and T7 heat treatment, the elongation of over 5% is obtained.

Key words: diesel engine cylinder head; high temperature tensile properties; aluminum alloys; modification; combination of strength and ductility

CLC numbers: TG146.21

Document code: A

Article ID: 1672-6421(2017)02-080-05

Diesel engines are used more and more widely in North America and Europe for passenger cars and light trucks because of their high fuel efficiency and reduced greenhouse gas emissions. These diesel engine components require a higher tensile property due to higher compression ratio and maximum breakout pressure of diesel engine compared with gasoline engines. Despite many advantages in the development of aluminum alloys, the alloys currently used for gasoline engine parts, typically A356 and 319 alloys, cannot meet the demand for high heat resistance^[1-5].

In our previous work^[6], we studied the influence of the secondary dendrite arm spacing (SDAS) as well as the combination of the SDAS and the heat treatment parameters on the mechanical properties of a cylinder head of A356 alloy. We found that the A356 alloy cylinder head with smaller SDAS reached its peak value

of hardness (HB), ultimate tensile strength (UTS) and yield strength (YS) at a lower aging temperature, but the over-aged structure was also yielded earlier. One of the most important factors that limit the use of A356 alloy for diesel cylinder head is its lower tensile properties at elevated temperatures: the properties of A356 (without Cu) alloy deteriorate seriously when temperature reaches $250\ ^\circ\text{C}$ ^[1-5]. The diesel cylinder head being developed requires an optimum combination of strength and elongation: $\text{UTS} \geq 290\ \text{MPa}$, $\text{YS} \geq 240\ \text{MPa}$, percent elongation $\geq 4.5\%$ and HB from 95 to 125, and for gravity casting, a value of SDAS not higher than 25 micron in the combustion chamber. To meet these requirements, we selected a candidate alloy containing copper - AlSi9Cu1 to produce the diesel cylinder head.

The chemical compositions of the commercial AlSi9Cu1 are very similar to alloy 354 of the AFS (the American Foundrymen's Society). It is an alloy used by the Cummins Company for diesel engine cylinder heads. The increased silicon content contributes to its excellent castability. Its excellent fluidity and resistance to hot cracking make it possible to produce castings larger in size and more intricate in design. Its copper content, from 0.8% to 1.3% in standard, allows it to have a

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Received: 2016-07-10; Accepted: 2016-12-19

higher hardness than A356 alloy. At the same time, compared with another commonly used alloy in automotive - 319 alloy, because of its lower iron and copper content, AlSi9Cu1 alloy can have greatly improved tensile and elongation properties. The problem we met in the test on cylinder head castings was that the elongation was only about 2.5% while its strength reached about 300 MPa using commercial alloys of AlSi9Cu1. So, the experiment focuses on how to improve the elongation without further reducing the tensile strength, through the optimization of its chemical compositions.

In the AlSi9Cu1 cast alloy, the size and morphology of the eutectic Si have a significant influence on the mechanical properties. Therefore, various modification elements were used to change the acicular eutectic Si into a fibrous structure [7-11]. Na and Sr are usually applied and show good modification effect [7]. Besides, the Fe exists in the alloy as a long, thick needles/platelets β -Al₃FeSi intermetallic phase, which results in low mechanical properties, in particular, a low percent elongation. The tensile ductility of AlSi9Cu1 alloy is not only related to the modification elements and Fe content, but also to heat treatment, because for some intermetallic phases, such as Al₂Cu, the way to improve the strength is through the precipitation-hardening heat treatment.

Thus, the study on the tensile ductility improvement is focused on the following three aspects: the selection of modification elements, Sr or Na; the reduction of Fe content, and the design of heat treatment parameters.

1 Experimental procedure

Figure 1 shows the cylinder head casting for a diesel engine. The nominal chemical compositions of AlSi9Cu1 are listed in Table 1. Commercial AlSi9Cu1 alloy was melted at 750 °C in a graphite crucible using an electric induction furnace. 50 ppm (of the mass of AlSi9Cu1) Na or 90 ppm Sr modifiers were added in NaF compound or Al-Sr intermediate alloy into the molten metal at 720±5 °C. Then, the molten metal was stirred and degassed using dry pure nitrogen for 15 min with a graphite rotation degassing machine. The pouring temperature was 720±5 °C.

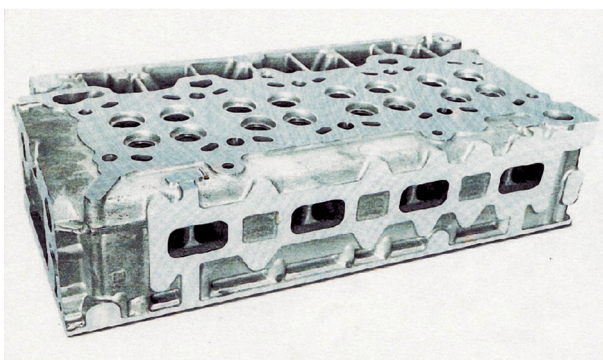


Fig. 1: Cylinder head for a diesel engine

Table 1: Nominal chemical compositions of AlSi9Cu1 (wt.%)

Si	Cu	Mg	Fe	Ti
9.0-10.0	0.80-1.30	0.25-0.50	≤0.30	≤0.10

All pouring tests of cylinder heads were performed on mass production equipment - FATA Gravity Casting Line and with the same SPM (Semi-Permanent-mold) tooling. The solidification time of all the cylinder heads was 270 s. To study the effect of Fe element on mechanical properties, two batches of commercial AlSi9Cu1 alloys were used to cast samples under the same conditions, one batch containing 0.27% Fe, and the other containing 0.10% Fe.

Heat treatment cycles were designed considering the over-aging of the castings, through high aging temperature (T7) or through prolonged time (T6).

Table 2: Heat treatment parameters

Heat treatment	Solution		Quenching	Aging	
	T (°C)	t (h)		T (°C)	t (h)
T6	515	6	Water 60 °C	160	12
	515	6		225	6
T7	515	6		245	6

The specimens for microstructure observation and tensile properties test were cut from the fire deck face of the cylinder heads, as shown in Fig. 2. Samples were machined in cylinder shape with a diameter of 10 mm. The tensile test was performed using a computer controlled ZWICK machine. A minimum of two castings (6 test-bars for each casting) were used. SDAS measurement was done on the fracture surface of tensile test bars after normal metallographic techniques of mounting, polishing and etching [12]. The SDAS value is the average of at least 4 measurements.

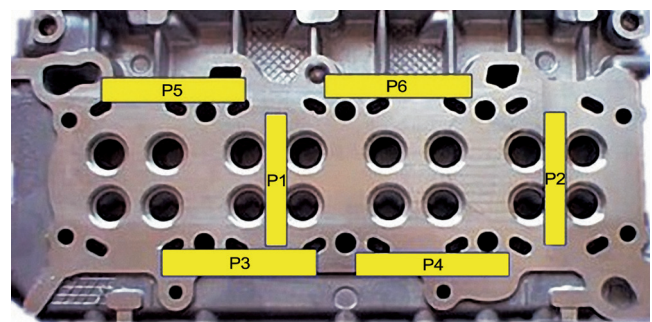


Fig. 2: Tensile test samples from fire deck face

2 Results and discussion

2.1 SDAS and tensile properties of AlSi9Cu1 alloy

Finer dendrite arm spacing is beneficial to mechanical properties of aluminum alloy castings. The SDAS value should be not higher than 25 μm in the combustion chamber according to the Engineering specifications for the cylinder head. The microstructure of the as-cast cylinder head produced from AlSi9Cu1 (0.27% Fe) modified with 90 ppm Sr is shown in Fig. 3, and the SDAS value is shown in Table 3.



Fig. 3: Microstructure of AlSi9Cu1 (0.27% Fe) alloy modified with Sr

Table 3: SDAS of AlSi9Cu1 (0.27% Fe) alloy modified with Sr

Sample number	SDAS (μm)	Average (μm)
1	17±1	
2	20±1	18±3
3	18±2	

As shown in Fig. 3, the secondary dendrite arms are well-distributed with a uniform size. The average secondary dendrite arm spacing is 18±3 μm, far less than 25 μm. Such results are consistent with the composition versus dendrite cell size curves produced by Spear and co-workers [13], which clearly showed the influence of four major alloying elements - Si, Cu, Mg, Zn on dendrite. The dendrite cell size decreases with the increase of alloying elements. In this work, the high silicon content and the

addition of Sr contribute together to lower the value of SDAS.

Figure 4 shows the ultimate tensile strength (UTS), yield strength (YS), hardness (HB) and elongation (E%) of the alloy modified with Sr after T6 and T7 heat treatments.

As shown in Figs. 4(a)–(c), UTS, YS and HB changed little when the aging parameters changed from 160 °C×12 h to 225 °C×6 h for AlSi9Cu1 alloy modified with Sr. These properties obviously decreased when the aging temperature increased to 245 °C, with the UTS of 276 MPa, YS of 208 MPa and HB of 88, respectively. The elongation values in the three different aging cycles ranged from 3.6% to 4.8%, much higher than the 2.5% of the as-cast AlSi9Cu1 alloy. Although we obtained a higher elongation as 4.8% with T7 (245 °C×6 h) heat treatment, the UTS, YS and HB can not meet the technical requirements for the cylinder head casting for the diesel engine. Considering the casting specification requirement and the severe service conditions of cylinder head, the effect of modification elements, Sr or Na and the influence of Fe content on tensile properties of AlSi9Cu1 alloy with T7 (225 °C×6 h) heat treatment were studied.

2.2 Effect of Na or Sr modification on tensile properties of AlSi9Cu1 alloy containing 0.27% Fe

Figure 5 shows the tensile properties of the Sr-modified AlSi9Cu1 alloy after T7 (225 °C × 6 h) heat treatment. It can be seen that the UTS and YS are not strongly affected by 50 ppm Na or 90 ppm Sr modification, but the modification in all the tests substantially improved the percent elongation of the alloy after the T7 heat treatment.

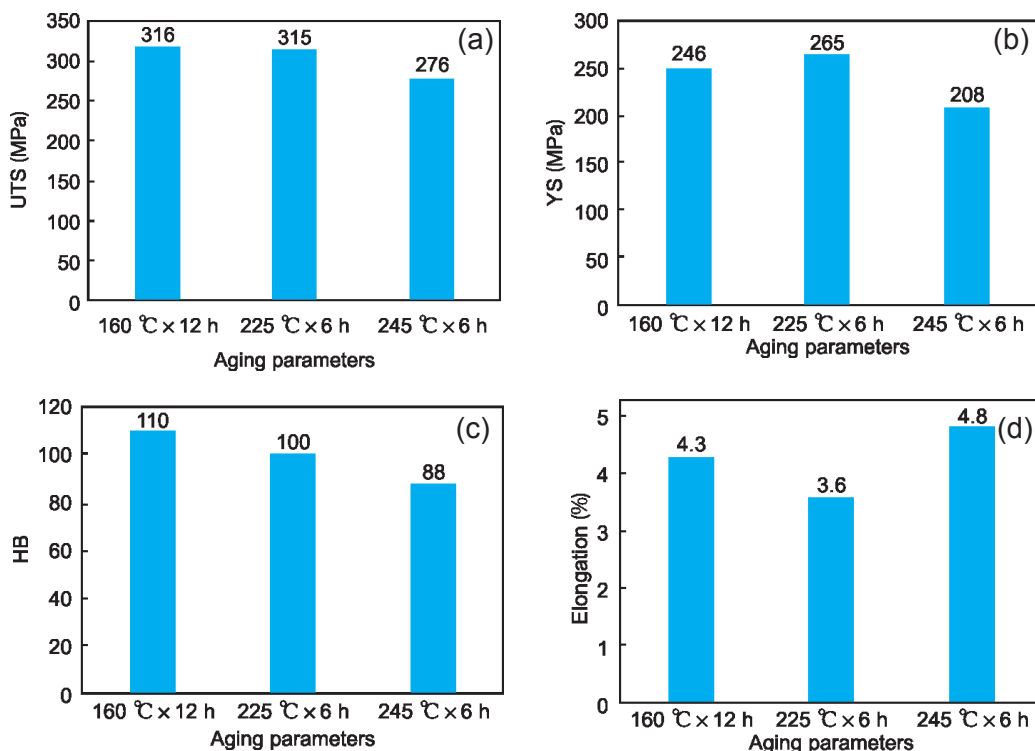


Fig. 4: Tensile properties of AlSi9Cu1 (0.27% Fe) alloy modified with Sr after T6 and T7 heat treatments: (a) UTS, (b) YS, (c) HB, (d) E%

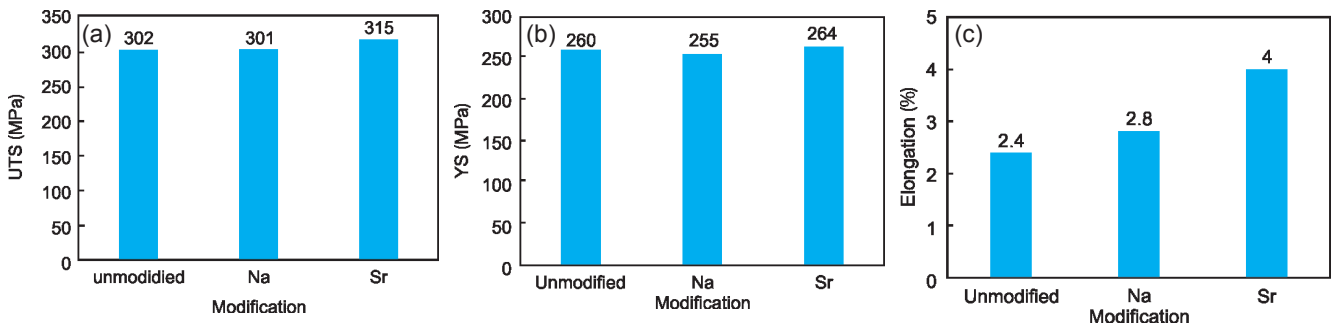


Fig. 5: Tensile properties of AISi9Cu1 (0.27% Fe) alloy sample after T7 heat treatment (225 °C×6 h): (a) UTS, (b) YS, (c) E%

Both Na and Sr modifications increased considerably the elongation of AISi9Cu1 cylinder heads. The elongation of alloy modified with Sr was increased by 66.7% compared with that unmodified one, from 2.4% to 4%, and by 42.9% compared with

that of Na modification, from 2.8% to 4%. Figure 6 shows the optical microstructures of the alloy with different modification elements.

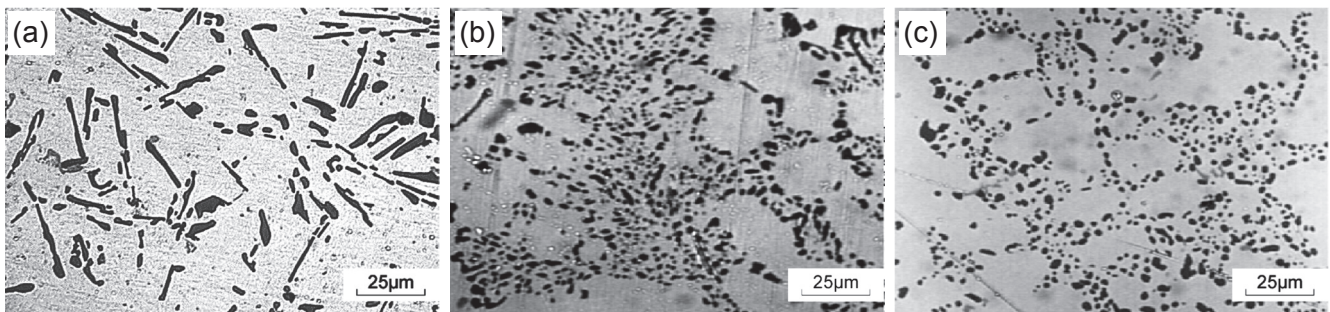


Fig. 6: Optical microstructures of AISi9Cu1 (0.27% Fe) alloy after T7 (225 °C×6 h) heat treatment: (a) unmodified, (b) modified with 50 ppm Na and (c) modified with 90 ppm Sr

As shown in Fig. 6(a), without modification, the microstructure of the AISi9Cu1 alloy mainly consists of acicular eutectic Si. In Fig. 6(b) - modified with 50 ppm Na and Fig. 6(c) - modified with 90 ppm Sr, the Si phase changes from bars to mesh, and the distribution of Si in Sr -modified alloy is more uniform than that modified with Na. After being modified with Sr, the needle, hard and brittle primary Si were broken into small fragments. The addition of Sr eliminates the inherent growth of the eutectic Si, resulting in a large number of high density twinned crystals, showing the twin growth mechanism.

The secondary dendrite arm of the alloy modified with Sr is also smaller than that modified with Na. It can be concluded that 90 ppm Sr has a better modification effect than 50 ppm Na for AISi9Cu1 alloy. It was well known that the finer microstructure can improve the tensile properties, elongation in particular.

Figure 5 also indicates that the alloy tensile properties were greatly improved by the addition of Sr.

2.3 Effect of Fe content on tensile properties of AISi9Cu1 alloy

Figure 7 shows the tensile properties of AISi9Cu1 (0.10% Fe) alloy after T7 heat treatment (225 °C × 6 h), confirming the results obtained on higher Fe (0.27%) alloy that Sr modification yields the best performances in percent elongation compared with Na. In the low Fe (0.10%) AISi9Cu1 alloy modified with Sr, the elongation after T7 heat treatment increases to more than 5%, and the alloy still maintains high ultimate tensile strength (>290 MPa) and yield strength (>240 MPa) values. The elongation is much higher than that of the alloy containing 0.27% Fe modified by Na or Sr after T7 heat treatment (Fig. 5c).

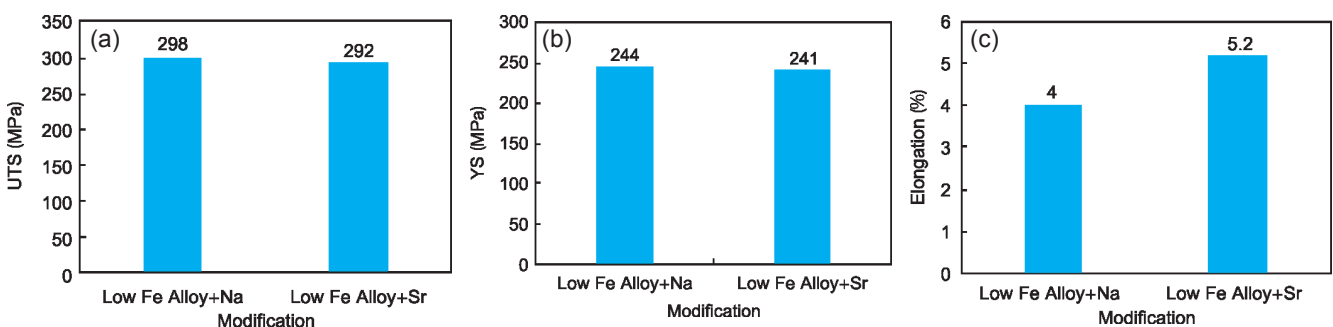


Fig. 7: Tensile properties of AISi9Cu1 alloy (0.10% Fe) after T7 heat treatment (225 °C×6 h): (a) UTS, (b) YS, (c) E%

A study on the role of trace elements in 319 alloy showed that increasing the iron content resulted in the precipitation of long, thick needles/platelets of the β -Al₃FeSi intermetallic phase^[14]. The increase of intermetallic needles/platelets would result in the decrease of percent elongation. Wu Xiaobo, et al^[15] studied the effect of Fe content from 0.12% to 1.91% as well as Fe phase morphology on the microstructure and mechanical properties of Al-Si Alloy. They found that with the increase of Fe content, tensile strength and elongation of castings were decreased, especially when the Fe content was from 0.12% to 0.97%. The morphology of Fe phase was mainly dominated by bone or needle shapes in high Fe content alloy, which resulted in the decrease of elongation.

3 Conclusions

Based on the results of the experiments, the following conclusions can be obtained:

(1) The 90 ppm Sr modified AlSi9Cu1 (containing 0.27% Fe) cylinder head has a low average SDAS as $18\pm 3\ \mu\text{m}$. The ultimate tensile strength (UTS), yield strength (YS) and hardness of the alloy remain a high level after T7 (225 °C×6 h) treatment, but obviously decrease when the aging temperature increases from 225 °C to 245 °C, which can not meet the technical requirements for the cylinder head, although the elongation reaches a high level of 4.8%. Therefore, T7 treatment (225 °C×6 h) is more applicable for the production of the AlSi9Cu1 cylinder head.

(2) Tensile test results show that Sr modification has no obvious influence on ultimate and yield strength properties, but it does improve the elongation values substantially for all tests. Sr addition results in higher elongation values than the Na modification. The elongation of the alloy with Sr modification increases by 66% compared with the unmodified alloy.

(3) AlSi9Cu1 alloy with a low Fe content (0.10%) gives good results in elongation; in particular, with Sr modification and T7 heat treatment at 225 °C, a high elongation of 5.2% can be obtained, while still maintaining the high values of UTS (292 MPa) and YS (241 MPa).

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This work was financially supported by the major project of Shandong Science and Technology (No. 2015ZDZX03004), the project of Shandong Science and Technology Development Plan (No. 2014GGX103035) and the National "Thousand Talents Plan" of China.