Aluminium alloys for cylinder heads

Aluminijeve zlitine za glave cilindrov

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Abstract: Nearly 100 % of all cylinder heads of the current light displacement vehicle production consist of aluminium cast alloys. The alloys have to sustain continuously growing requirements in terms of strength, ductility and heat resistance at an elevated temperature. Three different aluminium cylinder head alloys AlSi6Cu4, AlSi7MgCu0.5 and AlMg3Si1ScZr were examined and compared to each other with respect to fluidity, mechanical properties and hot cracking behaviour.

Izvleček: Skoraj 100 % vseh glav cilindrov aktualne proizvodnje avtomobilov je narejenih iz aluminijevih zlitin. Material glav cilindrov mora dosegati vedno večje zahteve po trdnosti, duktilnosti in obstojnosti pri visokih temperaturah. Preiskane so bile tri različne zlitine za izdelavo glav cilindrov AlSi6Cu4, AlSi7MgCu0.5 in AlMg3Si1ScZr ter med seboj primerjane glede livnosti, mehanskih lastnosti in nastanka razpok v vročem.

Key words: Al-Si alloy, cylinder heads, fluidity, mechanical properties
Ključne besede: Al-Si zlitine, glave cilindrov, livnost, mehanske lastnosti

Introduction

A contribution to reduce emission can be made by weight reduction, but at the same time an increase in power and torque are expected by the automotive customer[1].

Figure 1 shows the development of the power rating in diesel engine construction. Future developments will further aggravate this situation, because the next generation of diesel engines is likely to achieve a specific power rating of 75 kW/l and igniting pressures of 220 bars[2].

The cylinder head is one of the most complex and intensively loaded component in the engine (Figure 2). Not only camshaft

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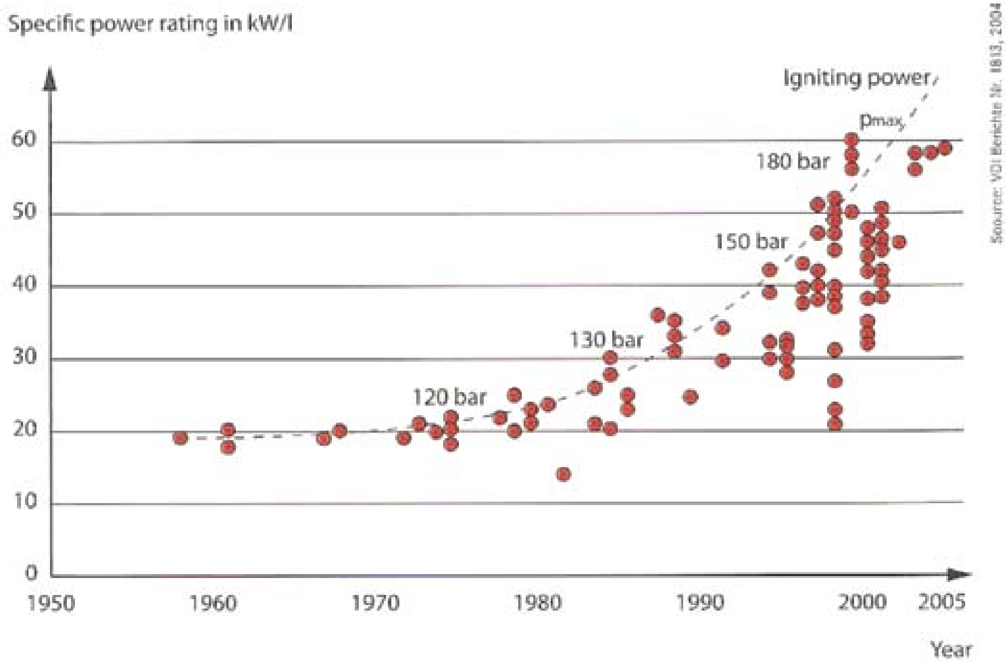


Figure 1. Development of the power rating and peak pressure in a car diesel engine[2]
Slika 1. Razvoj rasti moči in tlaka v avtomobilih z dizelskim motorjem[2]

Figure 2. Cylinder head[3]
Slika 2. Glava cilindra[3]

driven valves and combustion chamber, but also the camshaft bearing support is subjected to high stresses at high temperatures[2].

The aim of this research project was the comparison of two commercial heat resistant aluminium alloys AlSi7Mg0.5 and AlSi6Cu4, widely used in the production of cylinder heads, with a newly developed AlMg3Si1ScZr alloy. The following characteristics of the alloys were examined:

- mechanical properties at room temperature,
- mechanical properties at 250 °C,
- mechanical properties after 100 h pre-aging at 250 °C and tested at 250 °C,
- hot cracking behaviour,
- melt fluidity.

Experimental

Table 1 shows the chemical composition of the investigated alloys. For melting experiments an electric-resistance furnace with a crucible capacity of 3 kg was used. The melt was heated up to 720 °C and poured into several different test moulds.

Hot Cracking Behaviour

Hot cracking behaviour was defined with the star mould which is shown in Figure 3. The mould is made from gray cast iron and heated to 300 °C prior to casting.

Bars of different length are cast through a central gate in a star arrangement. These bars have thick portions at their ends, which obstruct shrinkage. The hot cracking behaviour was defined by evaluation of the cracks found[4]. For this, the castings were assessed visually by the number and relative importance of cracks or break-away bars using the following rating scheme (Figure 4):

- Number of full break-away rods × weighting factor 1,
- Number of wide circumferential cracks × weighting factor 0.75,
- Number of easily visible cracks × weighting factor 0.5 and,
- Number of hairline cracks (seen under the magnifying glass) × weighting factor 0.25.

Table 1. Chemical composition of investigated alloys in wt. % [3,4,5]

Tabela 1. Kemijska sestava preiskovanih zlitin v ut. % [3,4,5]

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
AlSi7MgCu	7.0	0.30	0.50	0.20	0.30	0.10	0.15	rest
AlSi6Cu	7.21	0.36	3.84	0.45	0.33	0.88	0.16	rest
AlMg3Si1(Sc,Zr)	1.09	0.08	0.003	0.012	3.29	0.001	0.02	rest

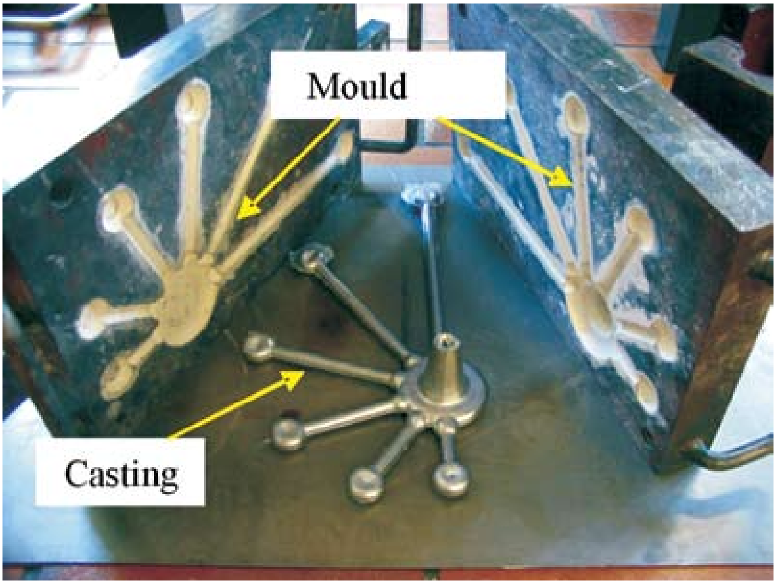


Figure 3. Star mould for assessment of hot cracking behaviour with star casting
Slika 3. Zvezdasta kokila z zvezdastim ulitkom za opazovanje razpok v vročem

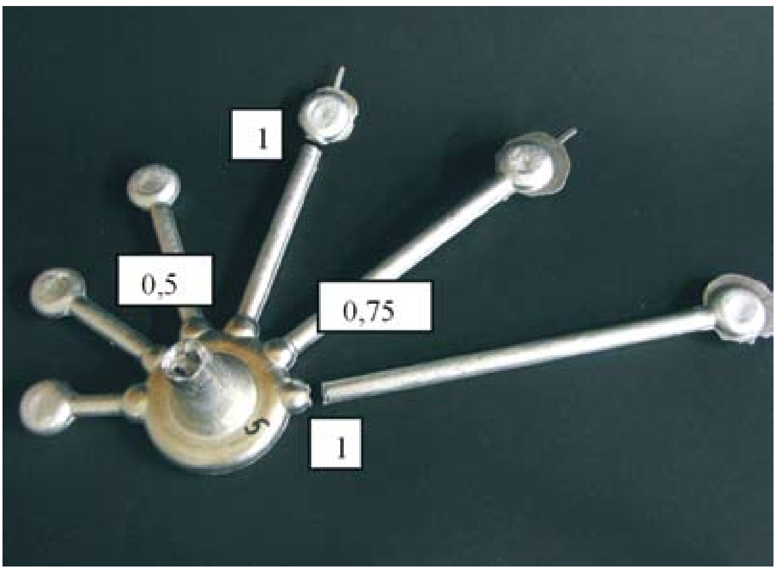


Figure 4. Star casting used to test hot cracking behaviour of the alloy
Slika 4. Zvezdasti ulitek za določitev razpok v vročem preiskovane zlitine

Definition of Fluidity

Fluidity is a material characteristic, telling how far a metal can flow in the mould and depends not only on the alloy's characteristics but also on the mould properties such as dimension, geometry, material, initial mould temperature, pouring temperature, etc. It is usually assessed as the total length of the branches filled with metal after solidification[6]. In this research an aluminium spiral mould heated up to 100 °C for determining the fluidity was used (Figure 5). The length of the spiral in cm after the experiment was measured.

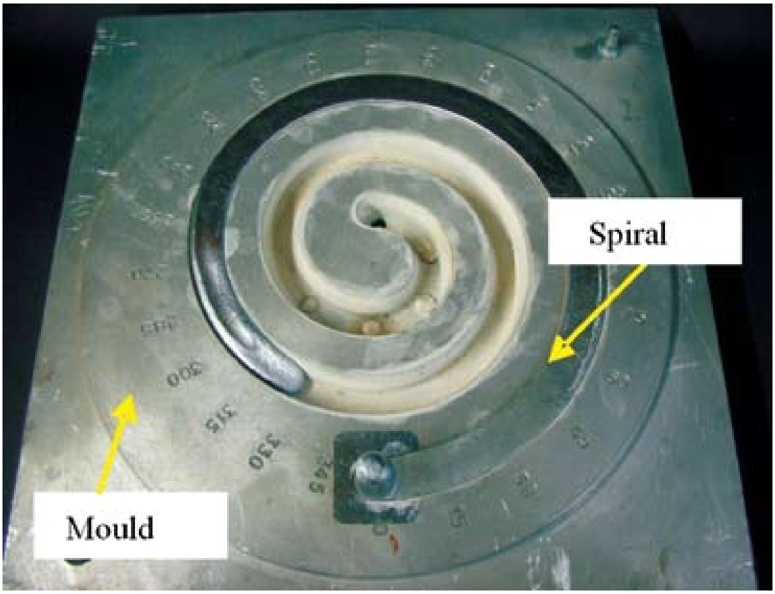


Figure 5. Mould for investigation of fluidity
Slika 5. Kokila za merjenje livnosti

Mechanical Properties

To study the mechanical properties a test specimen was used which was cast into a mould from gray cast iron according to DIN 29531 (Figure 6). The mould temperature was 300 °C. This mould provides castings that must be machined to the dimensions shown in Table 2. The tensile strength, yield strength and elongation were defined with tensile tests.

All alloys were T6 heat treated. Table 3 shows the heat treatment for each alloy. The samples were solution heat treated, quenched and hot age-hardened.

Table 2. Dimension of tensile test specimens
Tabela 2. Dimenzija vzorca za natezni preizkus

Specimens diameter d_0 [mm]	Coil d_1 [mm]	Head height h [mm]	Measurement length L_0 [mm]	Search length L_V [mm]	Total length L_T [mm]
6	M10	8	30	36	60

Table 3. Heat treatment for investigated alloys
Tabela 3. Toplotna obdelava preiskovanih zlitin

	AlSi7MgCu0,5		AlSi6Cu4		AlMg3Si1ScZr	
	Temperature [°C]	Time [h]	Temperature [°C]	Time [h]	Temperature [°C]	Time [h]
Solution treatment	530	6	505	6	505	10
	Water - quench		Water - quench		Water - quench	
Hot age-hardening	170	7	170	8	170	8

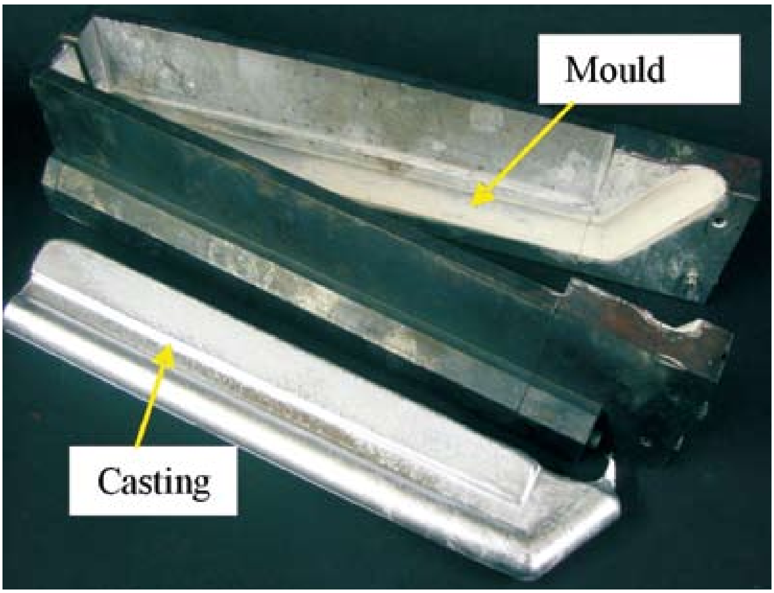


Figure 6. Mould and test bar according to DIN 29531
Slika 6. Kokila in preizkušanec po DIN 29531

RESULTS AND DISCUSSION

The results of the star mould casting are presented in Table 4. The higher the hot cracking index, the more likely is the alloy to develope hot cracks. The AlMg3Si1ScZr alloy reached the highest hot cracking index with 1.25.

Table 4. Hot cracking index of the investigated alloys
Tabela 4. Indeks razpok v vročem preiskovanih zlitin

Alloy	Hot cracking index
AlSi7MgCu0,5	0.75
AlSi6Cu4	0
AlMg3Si1ScZr	1.25

Table 5 shows the results of fluidity investigation. The best fluidity results show AlSi7MgCu0.5 alloy followed by AlMg3Si1ScZr and AlSi6Cu4 alloys.

Table 5. Fluidity of investigated alloys
Tabela 5. Livnost preiskovanih zlitin

Alloy	Length [cm]
AlSi7MgCu0,5	64.8
AlSi6Cu4	43.2
AlMg3Si1ScZr	52.5

The results of the tensile tests measured at room temperature are presented in Figures 7-9. Figure 7 evidently shows, that commercial alloys, AlSi6Cu4 and AlSi7MgCu0.5 and the newly developed AlMg3Si1ScZr alloy achieve similar values for tensile strength in as cast condition. After heat treatment the values for tensile strength of AlSi6Cu4 alloy rises to 408 MPa, AlSi7MgCu0.5 to 318 MPa and AlMg3Si1ScZr to 251 MPa.

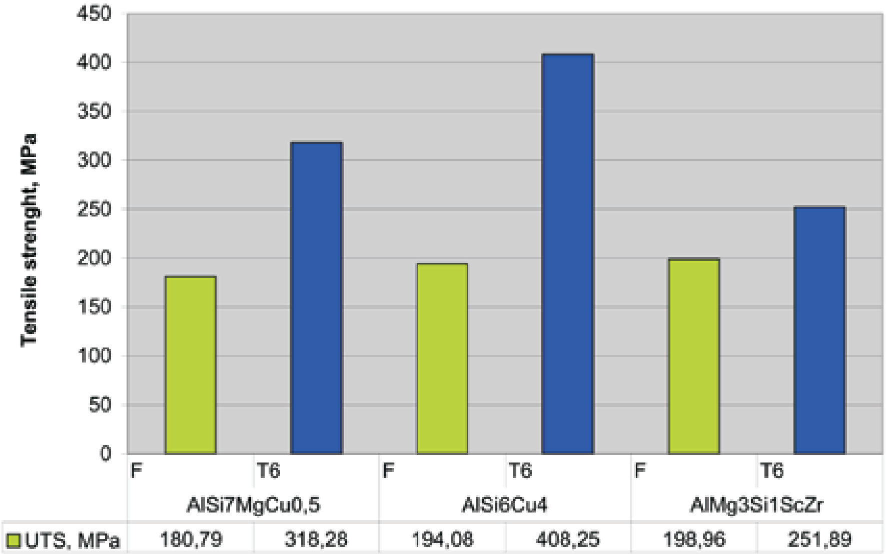


Figure 7. Tensile strength of investigated alloys, measured at room temperature (F – as-cast, T6 – heat treated)
Slika 7. Natezna trdost preiskovanih zlitin, merjena pri sobni temperature (F – lito stanje, T6 – toplotno obdelano stanje)

Figure 8 presents the yield strength of the investigated alloys. The AlSi6Cu4 alloy has a yield point of 136 MPa in as-cast condition. After heat treatment the yield point rises to 383 MPa. The yield point for AlMg3Si1Sc1Zr is 23 MPa higher then AlSi7MgCu0,5 in as-cast condition. But the yield point after heat treatment of the AlSi7MgCu0.5 alloy is higher than the AlMg3Si1ScZr alloy.

Figure 9 depicts the elongation of the investigated alloys. Obviously the best results in as-cast conditions showed the AlSi7MgCu0.5 alloy with an elongation of 6 %. After the heat treatment an increase of elongation values of 8.7 % can be detected. The AlMg3Si1ScZr alloy shows the best results after heat treatment with 10.7 %. The high strength AlSi6Cu4 alloy shows the poorest ductility.

The results of tensile tests at 250 °C of the investigated alloys are shown in Figure 10. The newly developed alloy AlMg3Si1SCZr shows by far the best elongation results with 16 % at 250 °C. But the tensile strength and yield strength of this alloy are comparable with commercial AlSi7MgCu0.5 alloy. The best tensile strength and yield strength results show AlSi6Cu4 alloy.

After pre-aging 100 hours at 250 °C the material performance at 250 °C is quit different. This test simulates the working condition in a cylinder head for a long period of time. Figure 11 evidently shows that AlMg3Si1ScZr alloy has the best results of all three investigated alloys. This alloy achieves a tensile strength of 251 MPa and the highest yield strength of 162 MPa.

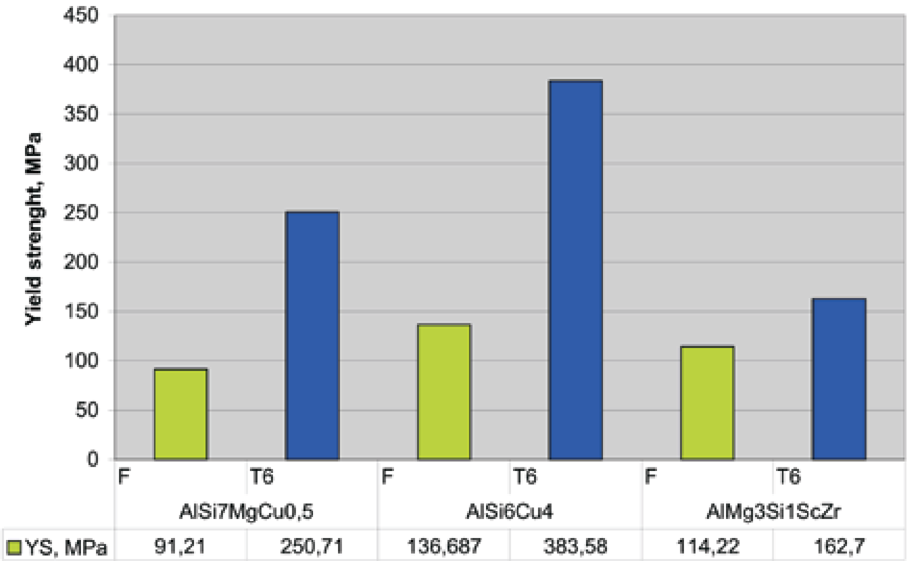


Figure 8. Yield strength of investigated alloys, measured at room temperature (F – as-cast, T6 – heat treated)
Slika 8. Meja tečenja preiskovanih zlitin, merjena pri sobni temperature (F – lito stanje, T6 – toplotno obdelano stanje)

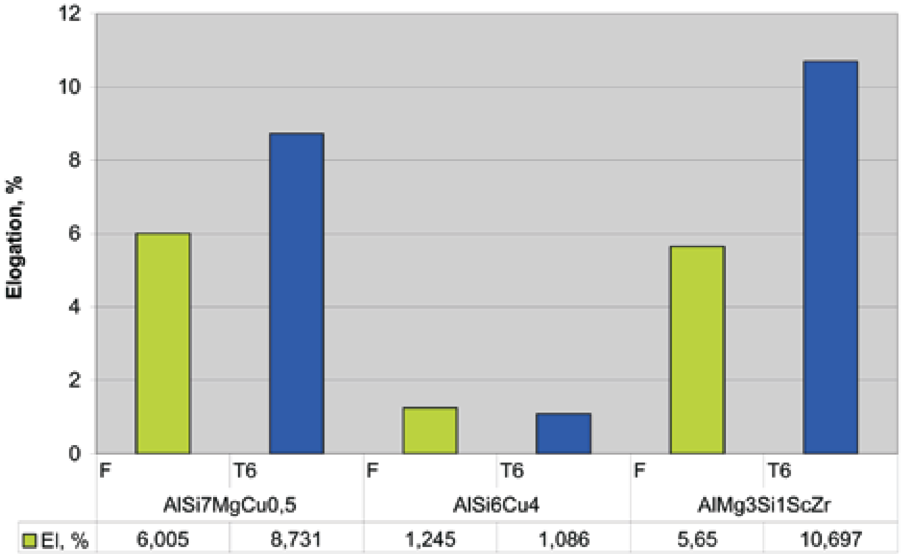


Figure 9. Elongation of investigated alloys, measured at room temperature (F – as-cast, T6 – heat treated)

Slika 9. Raztezek preiskovanih zlitin, merjen pri sobni temperature (F – lito stanje, T6 – toplotno obdelano stanje)

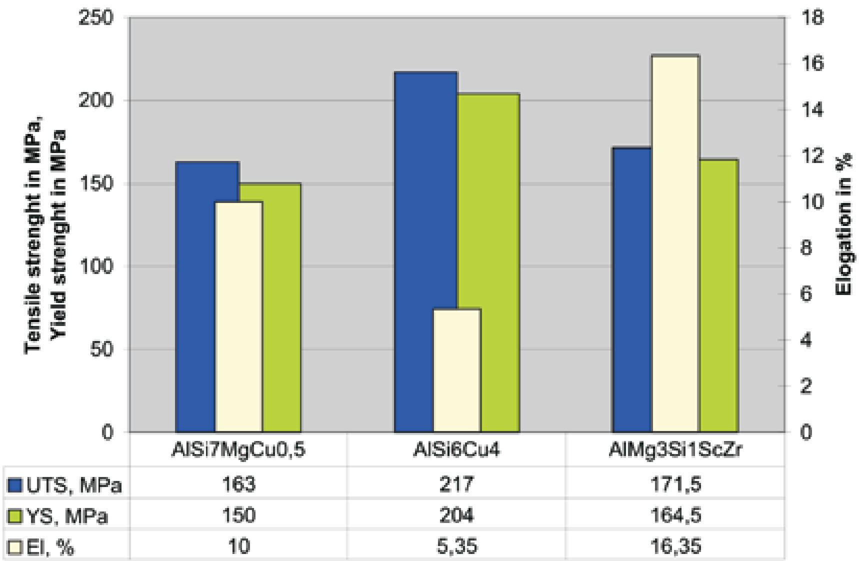
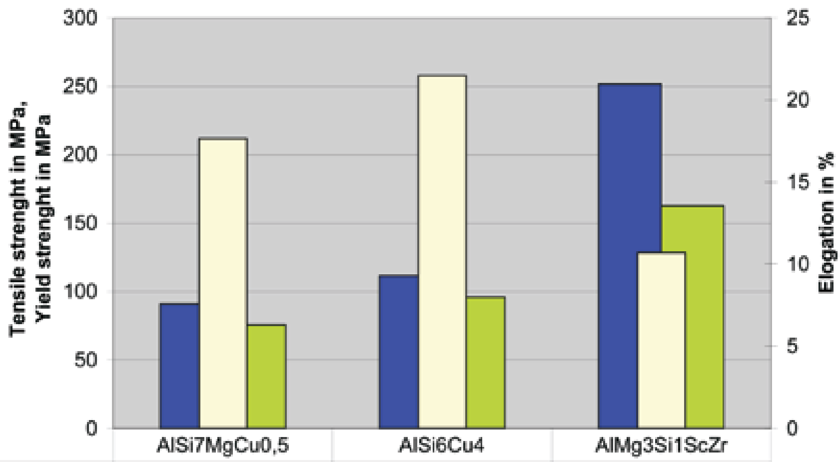


Figure 10. Tensile strength, yield strength and elongation of T6- heat treated alloys tested at 250 °C

Slika 10. Natezna trdnost, meja tečenja in raztezek T6 toplotno obdelanih zlitin, preizkus pri 250 °C



	AlSi7MgCu0,5	AlSi6Cu4	AlMg3Si1ScZr
UTS, MPa	91	111,5	251,89
YS, MPa	75,5	96	162,7
El, %	17,65	21,5	10,697

Figure 11. Tensile strength, yield strength and elongation T6-heat treated alloys tested at 250 °C, pre-aging 100 hours at 250 °C
Slika 11. Natezna trdnost, meja tečenja in raztezek T6 toplotno obdelanih zlitin staranih 100 ur na 250 °C, preizkus pri 250 °C

CONCLUSIONS

The AlMg3Si1ScZr alloy shows the best compromise of ductility and mechanical properties at 250 °C after pre-aging 100 hours at 250 °C, but it also shows the worst hot-tearing behaviour. The addition of Sc and Zr to the AlMg3Si1 base alloy has a positive effect on the mechanical properties, but on the other hand raises costs, which must be accepted by the industry. If 0.2 wt. % Sc is added to an alloy it will increase material cost to US$5/kg which, depending on the alloy, represents a doubling to quadrupling of the material cost[7].

The excellent tensile properties, fluidity and resistance to hot-tearing, allows the well known AlSi6Cu4 and AlSi7MgCu0.5 alloys to retain their leading position in the production of aluminium cylinder heads in the near future.

POVZETEK

Aluminijeve zlitine za glave cilindrov

Glave cilindrov so dan danes narejene izrecno iz aluminijevih zlitin in so ene izmed najbolj obremenjenih komponent v motorju. V tem delu so bile raziskane zlitine za izdelavo glav cilindrov. Preiskovale in primerjale so se dve poznani komercialni zlitini AlSi7MgCu0,5 in AlSi6Cu4 z novo razvito zlitino AlMg3Si1ScZr glede na mehanske lastnosti pri sobni temperaturi, po toplotni obdelavi in preizkusu pri 250°C in po 100 urnem staranju na 250°C in preizkusu pri 250°C. Preiskovale so se tudi livarske lastnosti, kot so nastank razpok v vročem in livnost zlitin. Pri mehanskih lastnostih so se opazovale natezna trdnost, meja tečenja in raztezek zlitine. Zlitine so bile ulite v zato pripravljeno kokilo iz sive litine po standardu DIN 29531. Ulitek se je nato obdelal na dimenzije za natezni preizkus. Nastanek razpok se je opazovalo s pomočjo zvezdaste kokile. Kokila je bila opremljena z petimi različno dolgimi palicami katerih konci so odebeljeni. Pri strjevanju prihaja do krčenja in zato do napetosti, kar posledica so razpoke. Razpoke so bile razdeljene v štiri razrede ter jim dodeljene vrednosti, in sicer indeks 1 za popolnoma odlomljeno palico, indeks 0,75 za razpoko, ki je potekala okrog palice, 0,5 za razpoko, ki je bila tako velika, da je bila vidna s prostim očesom in 0,25 za razpoko, ki je bila vidna le pod povečevalnim steklom. Vsi indeksi so bili nato sešteti in dobljen je bil indeks nastanka razpok v vročem. Livnost se je določevala s pomočjo spiralaste kokile. Kokila je bila izdelana iz aluminija in ob vsakem litju ogreta na 100 °C. Po končanem preizkusu je bila izmerjena dolžina spirale.

Zlitina AlMg3Si1ScZr je pokazala najboljšo kombinacijo duktilnosti in mehanskih lastnosti pri 250 °C po 100 urnem staranju na 250 °C, vendar tudi visok indeks nastanka razpok v vročem. Dodatka Sc in Zr imata pozitiven učinek na mehanske lastnosti, vendar prinašata visoke stroške, kar mora biti sprejeto s strani industrije. Dodatek 0,2 ut. % Sc zlitini poveča ceno zlitine za 5 $/kg.

Odlične lastnosti pri nateznem preizkusu, livnost in obstojnost v vročem, prinašajo zlitinam AlSi6Cu4 in AlSi7MgCu0,5 vodilno mesto pri proizvodnji aluminijastih glav cilindrov v bližnji prihodnosti.

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