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The effect of main alloying elements on the physical properties of Al–Si foundry alloys

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ABSTRACT

In this study we describe the effect of the main alloying elements Si, Cu and Ni on the thermal properties of hypoeutectic and near-eutectic Al–Si foundry alloys. By means of systematic variations of the chemical composition, the influence of the amount of 'second phases' on the thermal conductivity, thermal expansion coefficient, and thermal shock resistance is evaluated. Thermodynamic calculations predicting the phase formation in multi-component Al–Si cast alloys were carried out and verified using SEM, EDX and XRD analysis. The experimentally obtained data are discussed on a systematic basis of thermodynamic calculations and compared to theoretical models for the thermal conductivity and thermal expansion of heterogeneous solids.

1. Introduction

Today, power train components of modern transportation vehicles such as engine blocks or gearbox housings are frequently produced from recycled Al–Si foundry alloys on high-pressure die casting machines – a cost-efficient combination of material and process applicable for sustainable mass production. The accelerated need for weight reduction, however, leads to higher mechanical and thermal loading of these aluminium castings in future vehicles, requiring improved Al–Si foundry alloys. Therefore, in the last couple of years, several investigations were carried out with the objective of improving the mechanical properties of Al–Si foundry alloys at elevated temperatures [1–6].

However, it has taken a longer time to recognise the importance of the physical properties. In addition to high temperature strength, adequate thermal conductivity (TC) as well as low thermal expansion are crucial physical properties for alloys used as motor components. In case of pistons, e.g., the heat generated in the course of the compression process has to be removed as quickly as possible to avoid thermal stresses and hot spots on the surface, whereas low thermal expansion prevents the piston from becoming tight and seizing under operation temperature. TC as well as the coefficient of thermal expansion (CTE) can therefore play a major role in determining the life time of certain motor components [7].

TC is a measure of the rate at which heat is transferred through a material. It is mainly governed by electric conductivity, elastic vibrations of the lattice (phonons) and thermal consumption processes (specific heat). If the contribution of phonons is negligible (this is the case for pure metals), TC is mainly influenced by the mobility of electrons, i.e. the electric conductivity, σ_e.

It is well known that σ_e and thus TC is significantly decreased by the addition of alloying elements, whereupon elements in solid solution result in lower values than the same amount of elements forming intermetallic phases. The latter typically reduce thermal conductivity proportionally with increasing volume fraction [8].

The thermal expansion coefficient of alloyed metals often varies according to the expansion coefficients of the solute and the solvent elements. By alloying elements with a low CTE, the coefficient of the alloy can be decreased. Additions of Si, Cu and Ni reduce CTE in approximately a linear manner, whereas Mg or Zn can increase the expansion. Generally, the effects of alloying additions on thermal expansion are additive, following the rule of mixtures [9,10].

Since Si, Cu and Ni are the main alloying elements in Al–Si cast alloys used for high-temperature applications, the understanding of their effect on TC and CTE is fundamental defining reasonable concentrations of these elements in the respective alloys. Consequently, this work aims at quantifying the effect of single Si, Cu and Ni additions as well as their combined influence on TC and

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CTE of hypoeutectic and eutectic Al–Si foundry alloys and to compare several experimentally determined values with those obtained by classic theoretical models, predicting the physical properties of heterogeneous solids. Finally, a ranking of the particular alloys according to their resistivity to thermally induced strain shall be presented, facilitating the choice of alloys for engineering applications involving thermal stresses.

2. Experimental

2.1. Sample preparation

A series of 36 hypoeutectic and eutectic alloys based on the systems AlSi7 and AlSi12 were fabricated by the AMAG Austria Metall AG testing laboratory. The composition of the samples is shown in Table 1. The alloys are sectioned according to their Si content and Cu/Ni ratio: 1–16 (AlSi7(Mg)) and 17–36 (AlSi12(Mg)). Additionally, all alloys contain Fe and Mn in an amount comparable to recycling Al–Si foundry alloys.

All materials were melted in a 100 kg induction furnace and cast into a steel mould with a wall thickness of the test section of 20 mm to form tensile test bars. The mould was preheated to a temperature of 320 ± 5 °C and coated with boron nitride before casting, and the melt temperature was held constant at 750 ± 5 °C during the whole casting process. The alloys were solution-treated at 495 °C for 8 h and subsequently quenched in water at room temperature. Afterwards, the samples were over-aged at 250 °C for 100 h. This annealing procedure was performed in order to simulate the 'thermal load' in service.

2.2. Microstructure analysis

Metallographic specimens were cut out within the gauge length region of the cast samples to analyse the microstructure by means of light optical microscope (LOM) and scanning electron microscope (SEM) techniques. To identify the phase components occurring in the alloy, energy dispersive X-ray (EDX) and X-ray diffraction (XRD) analysis were performed. Thermodynamic calculations to evaluate the alloys' phase fractions were carried out using the Thermo-Calc software package with the data base TTAL5 [11].

2.3. Electric conductivity

Samples for measuring the electric and thermal conductivity with a diameter of 5 mm and a length of 30 mm were taken from tensile bars. The electric resistivity at room temperature was determined using a four-point current technique. When a constant current I flows from contact A to contact B it is possible to measure the voltage drop V across the contacts C and D in the middle of the sample and consequently calculate the electric conductivity σ_e of the material with

$$\sigma_e = \frac{Il}{UA} = \frac{l}{RA} \tag{1}$$

where R is the resistance and A the cross-sectional area of the specimen. All measurements were performed at a constant current of 7000 mA. The voltage drop was measured with a Hewlett Packard HP3456 digital voltmeter.

Table 1
Composition of the investigated alloys (in wt%).

Alloy nr.	Alloy	Si	Fe	Cu	Mn	Mg	Ni	Others
1	AlSi7(Mg)	6.93	0.40	< 0.05	0.30	0.36	< 0.05	< 0.05
2	AlSi7Ni0.5(Mg)	7.04	0.41	< 0.05	0.34	0.38	0.51	< 0.05
3	AlSi7Ni1(Mg)	7.24	0.39	< 0.05	0.30	0.40	1.06	< 0.05
4	AlSi7Ni1.5(Mg)	7.17	0.41	< 0.05	0.31	0.37	1.55	< 0.05
5	AlSi7Cu1(Mg)	7.06	0.40	0.98	0.31	0.37	< 0.05	< 0.05
6	AlSi7Cu1Ni0.5(Mg)	7.08	0.43	1.00	0.36	0.37	0.55	< 0.05
7	AlSi7Cu1Ni1(Mg)	7.20	0.41	1.00	0.31	0.37	1.06	< 0.05
8	AlSi7Cu1Ni1.5(Mg)	7.10	0.41	1.01	0.31	0.35	1.54	< 0.05
9	AlSi7Cu2(Mg)	7.14	0.40	2.09	0.31	0.35	< 0.05	< 0.05
10	AlSi7Cu2Ni0.5(Mg)	7.00	0.42	1.99	0.37	0.33	0.54	< 0.05
11	AlSi7Cu2Ni1(Mg)	7.14	0.40	2.11	0.31	0.35	1.00	< 0.05
12	AlSi7Cu2Ni1.5(Mg)	7.14	0.41	2.11	0.31	0.35	1.53	< 0.05
13	AlSi7Cu3(Mg)	6.90	0.40	3.06	0.31	0.34	< 0.05	< 0.05
14	AlSi7Cu3Ni0.5(Mg)	7.04	0.42	2.99	0.37	0.34	0.54	< 0.05
15	AlSi7Cu3Ni1(Mg)	7.01	0.42	3.01	0.37	0.34	1.01	< 0.05
16	AlSi7Cu3Ni1.5(Mg)	6.99	0.40	3.04	0.31	0.35	1.51	< 0.05
17	AlSi12(Mg)	12.15	0.43	< 0.05	0.32	0.34	< 0.05	< 0.05
18	AlSi12Ni1(Mg)	12.20	0.44	< 0.05	0.32	0.35	1.05	< 0.05
19	AlSi12Ni2(Mg)	12.33	0.44	< 0.05	0.31	0.35	2.11	< 0.05
20	AlSi12Ni3(Mg)	12.07	0.43	< 0.05	0.29	0.34	3.15	< 0.05
21	AlSi12Cu1(Mg)	12.05	0.39	0.95	0.29	0.34	< 0.05	< 0.05
22	AlSi12Cu1Ni1(Mg)	12.01	0.40	0.99	0.29	0.34	1.10	< 0.05
23	AlSi12Cu1Ni2(Mg)	12.04	0.40	0.99	0.29	0.35	2.05	< 0.05
24	AlSi12Cu1Ni3(Mg)	11.87	0.43	1.00	0.28	0.34	3.01	< 0.05
25	AlSi12Cu2(Mg)	12.05	0.41	1.96	0.30	0.34	< 0.05	< 0.05
26	AlSi12Cu2Ni1(Mg)	11.96	0.44	1.97	0.3	0.34	0.99	< 0.05
27	AlSi12Cu2Ni2(Mg)	11.94	0.44	2.02	0.29	0.35	2.02	< 0.05
28	AlSi12Cu2Ni3(Mg)	11.93	0.43	2.05	0.28	0.35	3.02	< 0.05
29	AlSi12Cu3(Mg)	12.26	0.40	3.02	0.3	0.35	< 0.05	< 0.05
30	AlSi12Cu3Ni1(Mg)	11.97	0.40	3.02	0.3	0.35	1.03	< 0.05
31	AlSi12Cu3Ni2(Mg)	12	0.40	3.05	0.29	0.35	2.12	< 0.05
32	AlSi12Cu3Ni3(Mg)	11.93	0.41	3.07	0.28	0.35	2.99	< 0.05
33	AlSi12Cu4(Mg)	12.02	0.43	3.79	0.30	0.32	< 0.05	< 0.05
34	AlSi12Cu4Ni1(Mg)	12.01	0.44	3.8	0.29	0.32	1.00	< 0.05
35	AlSi12Cu4Ni2(Mg)	12.02	0.46	3.87	0.28	0.32	1.99	< 0.05
36	AlSi12Cu4Ni3(Mg)	11.94	0.47	3.91	0.27	0.33	2.93	< 0.05