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THE INFLUENCE OF SOLUTION TREATMENT ON THE HIGH-TEMPERATURE STRENGTH OF AL-SI FOUNDRY ALLOYS WITH NI

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Abstract

Al-Si-Ni alloys can be considered as a coarse two-phase system where a hardening effect is caused by load transfer to an interconnected rigid network of eutectic Si and aluminides. In the course of a solution treatment the contiguity of the eutectic phase is reduced, which leads to a decrease of strength.
However, solution treatment is necessary to obtain a high supersaturation of elements in the Al-solid solution, which contribute to high-temperature strength due to precipitation hardening. Despite Ostwald ripening, the distribution of secondary precipitates is still dense enough to act as dislocation obstacles, as was confirmed by TEM-analysis.
This work discusses the influence of heat treatments on the elevated-temperature strength of Al-Si foundry alloys with Ni and analyzes the active strengthening mechanisms. In order to investigate the effect of a solution treatment on the high-temperature strength of Ni-containing Al-Si foundry alloys, the tensile properties of various eutectic alloys were determined at 250°C after long-time exposure to test temperature.

Introduction

Multicomponent Al-Si based foundry alloys provide several advantageous characteristics such as good castability, high corrosion and wear resistance as well as high thermal conductivity and adequate strength at elevated temperatures. Therefore they are widely used in automotive industry, especially for cylinder heads, pistons and gearbox housings [1-8].
The accelerated need for weight reduction, however, leads to higher mechanical and thermal loading of these aluminum castings in future vehicles, requiring improved Al-Si foundry alloys concerning strength at elevated temperatures [1-3, 7, 9].
For the development of new Al-Si recycling foundry alloys with superior elevated-temperature strength a detailed physical understanding of the role of each particular alloying element concerning its ability to improve the high-temperature properties is required. In previous work Ni was identified to significantly enhance the high-temperature performance of Al-Si foundry alloys, though just to a certain level, depending on the fraction of eutectic phase in the alloy. Ni stabilizes the contiguity of the eutectic network by increasing the volume fraction of rigid phases ($Si + Al_3Ni$) in the eutectic [8, 10-12].
Heat treatment (HT) is a commonly used technique to enhance the mechanical properties of the respective alloys, such as strength (HT: T6) or ductility (HT: T4, T7). However, during a solution treatment the eutectic Si spheroidizes and its aspect ratio decreases, which results in a loss of the contiguity of the eutectic platelets [8, 13].
Previous studies showed that in Ni-free alloys the Si contiguity is completely lost after a solution treatment at 540°C for 24 h, and (for example) an AlSi12 alloy changes from a 'fibre-reinforced' to a 'particle-reinforced' type of material, with the same strength as an AlSi1 alloy [8, 13].
Since heat treatment is energy-intensive and time-consuming it is generally desired to abstain from this expensive process, provided that the materials' performance concerning their mechanical properties is not severely affected. Consequently the aim of the present work is to analyze the effect of a solution treatment on the high-temperature strength of Ni-containing Al-Si foundry alloys and to clarify its effect on the active strengthening mechanisms.

Experimental Methods

Eight near-eutectic alloys based on the system AlSi12 with varying Ni concentration were fabricated by the AMAG Austria Metall AG testing laboratory. The composition of the samples is given in Table I. The alloys can be divided into two groups: Mg-containing (1 – 4) and Mg-free (5 – 8). 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.
The melt temperature was held constant at 750 ± 5°C during the whole casting process. The applied heat treatment involved a solution treatment at 495°C for 8 h and quenching into water at room temperature, and was carried out for the half of the samples which are marked by the abbreviation 'ST' in the following. In order to simulate the 'thermal load' in service all samples were over-aged at 250°C for 100 h.
Tensile test bars were designed according to the standard DIN60125:2004-01 (gauge length: 48 mm; diameter: 8 mm) and tested on a ZWICK universal tensile testing machine at 250°C using a strain rate of 0.006 sec^{-1}. The mechanical properties illustrated in the results section represent the average values of at least three separately cast rods.
Metallographic specimens were taken within the gauge length region of the tensile bars to analyze the microstructure by means of light optical microscope (LOM) and transmission electron microscope (TEM) techniques. To identify the phase components occurring in the alloy, energy dispersive X-ray (EDX) analysis was performed.

Table I. Chemical composition of the alloys (in wt%)

No.	Alloy	Si	Fe	Mn	Mg	Ni	Oth.
1	AlSi12(Mg)	12.15	0.43	0.32	0.34	-	<0.05
2	AlSi12Ni1(Mg)	12.20	0.44	0.32	0.35	1.05	<0.05
3	AlSi12Ni2(Mg)	12.33	0.44	0.31	0.35	2.11	<0.05
4	AlSi12Ni3(Mg)	12.07	0.43	0.29	0.34	3.15	<0.05
5	AlSi12	12.12	0.41	0.30	-	-	<0.05
6	AlSi12Ni1	12.27	0.42	0.29	-	1.08	<0.05
7	AlSi12Ni2	12.24	0.43	0.29	-	2.03	<0.05
8	AlSi12Ni3.5	12.27	0.39	0.35	-	3.55	<0.05

Experimental Results

In the following section, the influence of a solution treatment on the tensile properties at 250°C is illustrated from a phenomenological viewpoint. All specimens were tested and characterized in severe over-aged condition (annealed at 250°C for 100 h).

Tensile Properties

Figure 1 shows the results of tensile tests carried out on the Mg-containing alloys at 250°C after severe over-ageing at 250°C for 100 h. The plot of the mechanical properties against the Ni concentration reveals a significant improvement of the strength by the addition of Ni. Both yield and tensile strength show similar trends as can be clearly seen in Fig. 1. The high-temperature performance of alloy 1 (AlSi12(Mg)) seems to be considerably reduced when exposed to a solution treatment, whereas in the case of the Ni-containing alloys annealing at 495°C has a distinct positive effect, especially regarding yield strength.

The triangles in Fig. 1 represent uniform elongation, which decreases up to 2% Ni. Please note that here we focus mainly on the influence of a solution treatment on the high-temperature strength, and do not discuss an effect on ductility (the A_g values are still shown in the results section).

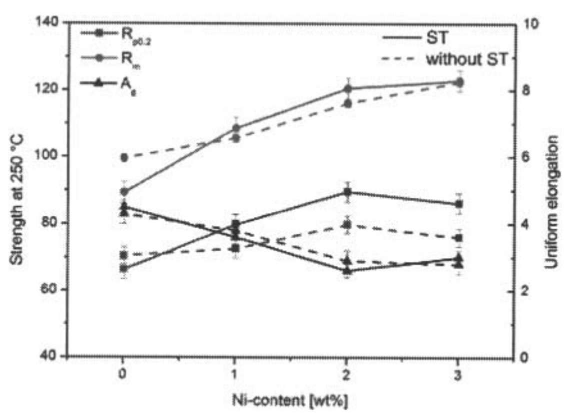

Figure 1. Mechanical properties of the Mg-containing alloys 1 – 4 measured at 250°C after long-term exposure to 250°C for 100 h.

Figure 2 illustrates the influence of a solution treatment on the Mg-free alloys depending on their Ni content. Obviously, in this case a solution treatment has a negative effect on the high-temperature strength, especially concerning tensile strength.

Although a linear increase of strength with increasing Ni content can be observed, the yield strength of the solution-treated alloys starts at a significantly lower value and approaches the as-cast alloys with increasing Ni content, until at a Ni concentration of 3% the yield strength levels are almost the same. The tensile strength of the solution-treated alloys starts at a value of more than 10 MPa lower compared to the as-cast samples. This deviation remains more or less constant with increasing Ni concentration.

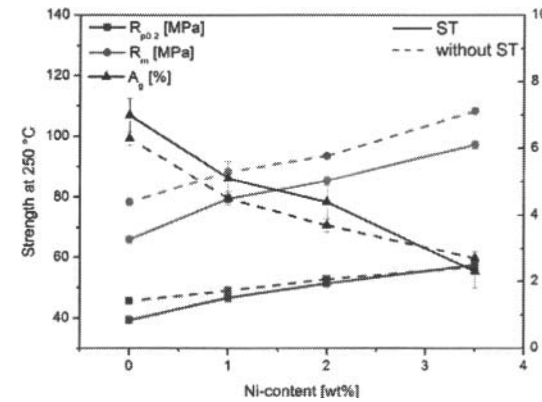

Figure 2. Mechanical properties of the Mg-free alloys 5 – 8 measured at 250°C after long-term exposure to 250°C for 100 h.

Microstructural Analysis

Light Optical Microscopy (LOM). Figure 3 shows LOM micrographs of the Mg-containing alloys 1 and 3. Five different phases can be observed: α-Al (a), primary Si (b), eutectic Si (c), Fe(Mn)-constituents (d) and Ni-containing phases (e). By means of EDX-analysis the latter were identified to be Al_3Ni- and Al_9FeNi-phases, respectively.

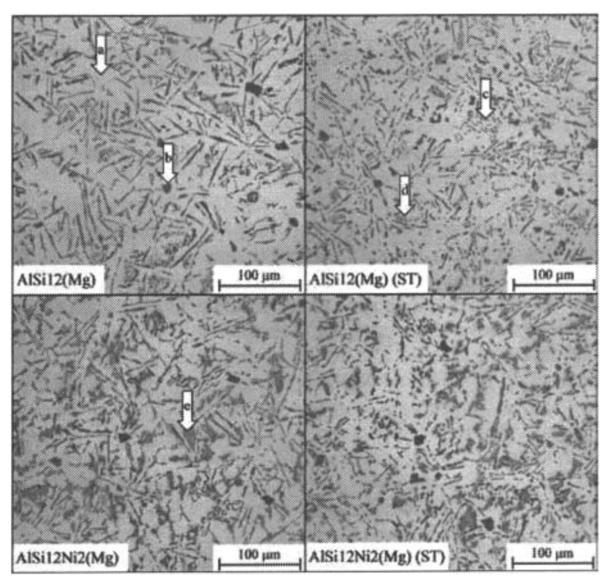

Figure 3. LOM micrographs of alloys 1 and 3, in as-cast (left) and solution-treated (right) state. All samples were severely over-aged at 250°C for 100 h.

As a result of solution treatment spheroidization of the eutectic Si takes place and its aspect ratio decreases. In contrast, the Ni-containing phases do not significantly change their shape.

Transmission Electron Microscopy (TEM). Figure 4 shows a bright field (a) and a dark field (b) TEM image of the Mg-containing eutectic alloy 1 (AlSi12(Mg)). The dominant phases are thin and elongated rod-shaped precipitates which were analyzed to be Mg_2Si (β-phase). Their average interparticle spacing is about 300 nm. Details of the TEM investigation will be published elsewhere.

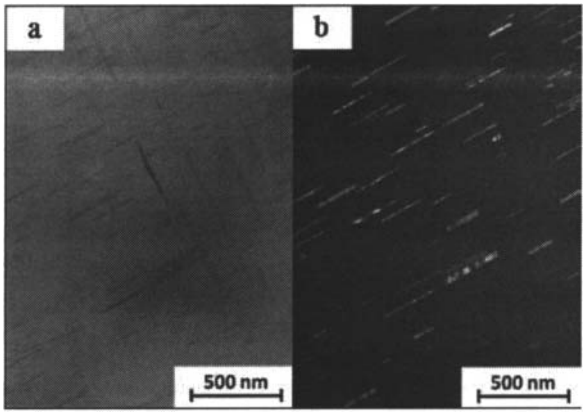

Figure 4. (a) Bright field and (b) dark field TEM image of alloy 1 (495°C/8 h + 250°C/100 h), showing predominantly Mg_2Si-precipitates (β-phase).

Discussion

In this work the mechanical properties of 8 eutectic alloys based on the systems AlSi12(Mg) and AlSi12 were determined at a temperature of 250°C after long-term exposure for 100 h to the test temperature. It was shown that Ni significantly increases the strength at elevated temperatures (Fig. 1 and 2). However, if the alloys are subjected to a solution treatment a significant difference between the Mg-free and the Mg-containing alloys concerning high-temperature strength can be observed.
In the following section we analyze the effect of a solution treatment on the mechanical properties at elevated temperatures by discussing the single influence of Ni and Mg on the high-temperature strength and the combined effect of both elements, respectively.

The Effect of Ni

The effect of Ni on the high-temperature strength of Al-Si foundry alloys was discussed in detail elsewhere [10-12]. It was shown that the whole microstructure of Al-Si alloys can be considered as a coarse two-phase system, with the phases 'primary Al solid solution (α_{prim})' and 'eutectic (E)' [10-12].
When comparing the hardness or strength of these phases qualitatively, one can assume E to be the stronger/harder phase. In coarse two-phase systems the stronger phase will contribute significantly to the overall strength only if it is subjected to load transfer. Load transfer, however, requires a continuous network of the respective phase. Such continuity of the harder phase E undoubtedly exists for the microstructures of the alloys investigated [10-12].

We now have to consider the microstructural features within the eutectic. In Ni-containing alloys the eutectic phase E consists of more or less soft 'eutectic Al (α_E)' and hard 'eutectic Si and Al_3Ni'. The eutectic phase E can therefore also be treated as a composite, with the same requirements as discussed above for the α_{prim} + E-compound. In order to form a strong/hard E-phase the hard 'eutectic Si and Al_3Ni' needs to be connected 3-dimensionally [10-12].
In Ni-free alloys the Si contiguity is completely lost after a solution treatment at 540°C for 24 h and an AlSi12 alloy e.g. changes from a 'fibre-reinforced' to a 'particle-reinforced' type of material, with the same strength as an AlSi1 alloy [8, 13].
When Ni is added to the Al-Si system, the eutectic transformation is characterized by a simultaneous formation of eutectic Si and Al_3Ni and consequently, eutectic Si and Al_3Ni form a geometrically entangled system. During the course of a solution treatment eutectic Al_3Ni does not significantly change its shape, as can be metallographically observed (see Fig. 3). Furthermore, in the presence of Ni-aluminides the loss of interconnectivity of eutectic Si is significantly reduced [10-12].
The Ni-phase in combination with eutectic Si forms a strongly interconnected 3D-structure, whose contiguity is highly preserved even after a solution treatment for 24 h [8]. However, depending on the amount of eutectic phase, more or less Ni is required to restore the connectivity of the 'eutectic Si + Al_3Ni' network. For Mg-containing eutectic alloys the authors determined 2% Ni to be sufficient to sustain the contiguity of solution-treated samples, and an increase in the Ni concentration has no further positive effect on strength [10-12].
For this reason the high-temperature strength of the Mg-containing alloys 1 – 4 increases with increasing Ni concentration up to 2%, whereas the positive effect of Ni is much more considerable for the solution-treated alloys, especially with respect to the yield strength. While for Ni-containing alloys the contiguity of the 'eutectic Si and Al_3Ni' is more or less preserved due to the presence of Ni-aluminides, the spheroidization of the eutectic Si in the Ni-free alloy 1 (AlSi12(Mg)) results in its reduced contiguity and thus reduced strength values.
Interestingly, in contrast to the Ni-free alloy 1 for the Ni-containing variants (2 – 4) a solution treatment has a distinct positive effect, especially regarding the yield strength. Interpreting the results only in consideration of the contiguity theory can not sufficiently explain this effect but requires in addition the assessment of Mg_2Si formation, which is done in the next section.

The Effect of Mg

The near-eutectic alloys 1 – 4 are Cu-free and no intermetallic phase containing both Ni and Mg is known. As a consequence Ni is bond in Al_3Ni and Al_9FeNi (as was confirmed by EDX-analysis) and Mg forms the Mg_2Si phase or contributes to strength by solid solution hardening.
In another article the authors showed that Mg_2Si-dispersoids precipitate in the course of artificial ageing and coarsen with increasing over-ageing duration [12]. After the applied over-ageing treatment at 250°C for 100 h the interparticle spacing of the β-phase lies in the range of 300 nm (see Fig. 4). According to Orowan-strengthening of shear-resistant precipitates they still contribute to an increase in elevated-temperature strength [12].
However, it is a reasonable assumption that the coarsening of precipitates due to Ostwald ripening is not completely finished after over-ageing at 250°C for 100 h.

As growth of Mg_2Si will slow down exponentially with increasing ageing duration, the contribution of the secondary precipitates to strength at elevated temperatures will monotonically decrease.

If Mg is after all considered as an element, which can enhance the alloys' high-temperature strength by the precipitation of secondary Mg_2Si-phases, a solution treatment is certainly required to supersaturate the entire amount of Mg in the α-solid solution, which is why the yield strength of alloys 2 – 4 is significantly higher for the solution-treated samples. However, a comparison of the as-cast variants 1 and 5 (AlSi12(Mg) and AlSi12) shows, that the strength values start at a considerably higher level for the Mg-containing alloy. Therefore it can be assumed, that a substantial part of Mg is already supersaturated in the α-solid solution during the solidification process.

Let us now go back to Fig. 1. Assuming, that in the case of AlSi12Ni2(Mg) (alloy 3) and AlSi12Ni3(Mg) (alloy 4) the network of hard phases (Si and Al_3Ni) in the eutectic is completely continuous for the as-cast as well as for the solution-treated samples, the increase of about 10 MPa in yield strength of the solution-treated samples compared to the as-cast counterparts can only be ascribed as a consequence of Orowan-hardening by β-Mg_2Si-precipitates.

In case of AlSi12Ni1(Mg) (alloy 2) the difference in yield strength is slightly reduced, most likely as a consequence of a light decrease in contiguity caused by the solution treatment. The contiguity of Ni-free AlSi12(Mg) (alloy 1) is obviously significantly reduced as a result of annealing at 495°C. Yield and tensile strength of the solution-treated alloy are even 4 MPa and 10 MPa lower compared to the 'as-cast' variants. This leads to the assumption, that the influence of the contiguity of the eutectic Si is crucial in the case of the Ni-free alloy and cannot be fully compensated by the precipitation of Mg_2Si-phases.

The performance of the Mg-free alloys (Fig. 2) is significantly different compared to the Mg-containing variants. The yield strength values of the as-cast samples always lie above those of the solution-treated variants, which is in accordance with the contiguity hypothesis: solution treatment leads to a reduction in contiguity of the hard eutectic phases.

Due to the contiguity-restoring effect of Ni the negative effect of a solution treatment declines with increasing Ni content until at a Ni concentration of 3.5% the yield strength of both the as-cast and solution-treated samples are identical.

It is important to note that the strength of the Mg-free alloys further increase when the Ni content is enhanced from 2% to 3.5%, while 'saturation' was observed at a Ni content of 2% for the Mg-containing alloys. Thus, it can be assumed that in Mg-containing alloys Mg does take part in forming the network of hard phases, most probably as heterogeneous-nucleated Mg_2Si formed at the Si-Al_3Ni-matrix interface during ageing.

Interestingly, we observed a significant effect of the solution treatment on the work hardening performance of the alloys. The difference between yield and tensile strength was always higher for the alloys without solution treatment, even in case of lower uniform elongation, and independent on the Ni content and thus contiguity. Further work aiming at a clarification of this phenomenon is in progress and will be reported elsewhere.

Conclusions

The objective of this study was to investigate the influence of a solution treatment on the high-temperature strength of Ni-containing Al-Si foundry alloys.

During a solution treatment the eutectic Si platelets spheroidize and their aspect ratio decreases, which results in a loss of the contiguity of the eutectic phases. For this reason a solution treatment has a negative effect on the high-temperature strength of non age hardenable Al-Si foundry alloys.

For Mg-containing Al-Si alloys a solution treatment is required to supersaturate Mg in the Al-solid solution, which is subsequently precipitated during over-ageing in the form of secondary Mg_2Si-phases. These phases increase the high-temperature strength by Orowan-hardening.

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References

1. Y.-H. Cho et al.: "The Effect of Alloying Elements on the Microstructure and Mechanical Properties of Al-12Si Cast Alloys", Mater. Sci. Forum, 426-432 (2003), 339-344.
2. Y.-H. Cho et al.: "The Effect of Alloy Addition on the High Temperature Properties of Over-aged Al-Si(CuNiMg) Cast Alloys", Mater. Sci. Forum, 519-521 (2006), 461-466.
3. Z. Qian et al.: "Effects of trace Mn addition on the elevated temperature tensile strength and microstructure of a low-iron Al-Si piston alloy", Mater. Letters, 62 (2008), 2146-2149.
4. M. Zeren: "The effect of heat-treatment on aluminum-based piston alloys", Materials and Design, 28 (2007), 2511-2517.
5. C.-L. Chen et al.: "Mechanical properties of intermetallic phases in multi-component Al-Si alloys using nanoindentation", Intermetallics, 17 (2009), 634-641.
6. C.-L. Chen et al.: "Investigation of mechanical properties of intermetallic phases in multi-component Al-Si alloys using hot-stage nanoindentation", Intermetallics, 18, Issue 4 (2009), 499-508.
7. Y. Li et al.: "Quantitative comparison of three Ni-containing phases to the elevated-temperature properties of Al-Si piston alloys", Mater. Sci. and Eng. A, 527 (2010), 7132-7137.
8. Z. Asghar et al.: "The role of Ni and Fe aluminides on the elevated temperature strength of an AlSi12 alloy", Mater. Sci. and Eng. A, 527 (2010), 5691-5698.
9. Klan S.: "Beitrag zur Evolution von Aluminium-Gusslegierungen für warmfeste Anwendungen", Fakultät für Werkstoffwissenschaft und Werkstofftechnologie der technischen Universität Bergakademie Freiberg, Freiberg (2004).
10. F. Stadler et al.: "The effect of Ni on the high-temperature strength of Al-Si cast alloys", Mater. Sci. Forum, 690 (2011), 274-277.
11. F. Stadler et al.: "Der Einfluss von Nickel auf die Warmfestigkeit von AlSi-Gusslegierungen", Giesserei, 98 (2011), 26-31.
12. F. Stadler et al.: "The effect of main alloying elements on the strength of Al-Si cast alloys at elevated temperatures", to be published.
13. F. Lasagni et al.: "Three-dimensional characterization of 'as-cast' and solution-treated AlSi12(Sr) alloys by high-resolution FIB tomography", Acta Mater., 55 (2007), 3875-3882.