

# Effect of Ni additions on A356 alloy's microstructure and high-temperature mechanical properties

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*This paper investigates the effect of three different Ni additions (0.5, 1 and 2 wt%) on the high-temperature tensile properties of the commercial purity unmodified A356 (Al-7 wt% Si-0.3 wt% Mg) aluminium foundry alloy. As-cast and T6 heat-treated tensile samples, obtained by permanent mould casting, have been tested at 508 K (235 °C). Fracture profiles and surfaces have been observed via optical and scanning electron microscopy to analyse the failure mechanism. It was observed that Ni contents higher than 0.5 wt% cause a remarkable decrease in yield strength and ultimate tensile strength of the T6 heat-treated alloys, which therefore become comparable with the tensile properties of the corresponding as-cast alloys. According to microstructural observations, the early rupture of fragile Ni-rich intermetallic phases seems to govern the fracture process of these alloys, neutralising the positive effect of the heat treatment.*

**KEYWORDS:** ALUMINIUM ALLOYS - CASTING - NICKEL ADDITION - TENSILE PROPERTIES - ELECTRON MICROSCOPY

## INTRODUCTION

Aiming at reducing weights, fuel consumption and exhaust emissions, automotive manufacturers have been increasingly using

Al-Si casting alloys in their vehicles. Among such alloys, the hypoeutectic A356 alloy (Al-7 wt% Si-0.3 wt% Mg) is one of the most widely employed for critical structural applications due to a combination of beneficial metallurgical and manufacturing characteristics, such as good mechanical properties in the heat-treated condition [1,2], corrosion resistance [3] and excellent castability [4]. However, mechanical properties of the A356 alloy rapidly decrease with increasing temperature, which makes it unsuitable for applications where high-temperature performances are needed, e.g. automotive engines.

The addition of specific alloying elements such as Ni and/or Cu has proven to be an effective way to increase the elevated-temperature properties of commercial grade A356 alloy. The formation of several complex intermetallic compounds that are thermally stable, such as the  $Al_3Ni$ ,  $Al_3CuNi$ ,  $Al_7Cu_4Ni$  and  $Al_9FeNi$  phases, allows the alloy to hold remarkable mechanical properties, especially when the temperature is beyond 523 K (250 °C) [5-9]. On the other hand, when the sole Ni is added, only  $Al_3Ni$  and  $Al_9FeNi$  intermetallic phases are formed during solidification depending on the alloy's purity [1,10-13]. In particular, it has been observed that Ni concentrations of approximately 1 wt% lead to the formation of a rigid long-range three-dimensional structure consisting of eutectic Si and Ni-bearing aluminides, whose contiguity is preserved even after the heat treatment [11,12]. As a result, the yield strength of the A356 alloy is enhanced by approximately 30 MPa (+70 %) at 250 °C [11].

In a recent work, Di Giovanni et al. have shown that the addition of Ni in traces (600 ppm) has no influence on the high-temperature tensile properties of the unmodified A356 alloy in both as-cast and T6 heat-treated conditions [13]. Ac-

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According to microstructural observations [1,10,13], this concentration is evidently insufficient to form a thermally stable interconnected 3D network of eutectic Si and Ni-containing phases. The aim of this work is thus to study the effect of increasing Ni additions (namely 0.5, 1 and 2 wt%) on the high-temperature strength of the commercial purity unmodified A356 aluminium foundry alloy. Tensile tests have been performed at 508 K (235 °C) on as-cast and T6 heat-treated samples. Subsequently, preliminary microstructural and fractographic analyses have been carried out to evaluate the contribution of the rigid phases to the strengthening of the alloy and to investigate the microstructural features involved in the fracture process.

## MATERIALS AND METHODS

A commercial purity A356 alloy was melted in a boron-nitride coated clay-graphite crucible at 1013 K (740 °C). Ni was added to the melt from an Al-10 wt% Ni master alloy according to the targeted nominal concentrations of 0.5, 1 and 2 wt%, and held for 10 min to have complete dissolution. Melts were then degassed with argon gas for 10 min just prior to casting. Permanent mould castings were obtained by pouring the molten alloy into an L-shaped preheated steel mould [1], manufactured according to the UNI 3039 specification. The temperature of the die was kept at 573 K (300 °C) during the casting trials. Samples from the three different melts were taken and analysed by glow discharge optical emission spectroscopy (GD-OES). The chemical composition of the alloys is given in Table 1.

**Tab. 1** - Chemical composition (wt%) of the alloys as measured by GD-OES and their classification.

NI-CONTAINING ALLOYS: CHEMICAL COMPOSITIONS, CONDITIONS AND CODES							
Alloy	Si	Fe	Mg	Ni	Al	Condition	Alloy Code
A356 + 0.5 wt% Ni	6.64	0.08	0.24	0.44	bal.	As-cast	Ni0.5-AC
						T6	Ni0.5-T6
A356 + 1 wt% Ni	6.87	0.08	0.25	0.95	bal.	As-cast	Ni1-AC
						T6	Ni1-T6
A356 + 2 wt% Ni	7.13	0.08	0.23	1.88	bal.	As-cast	Ni2-AC
						T6	Ni2-T6

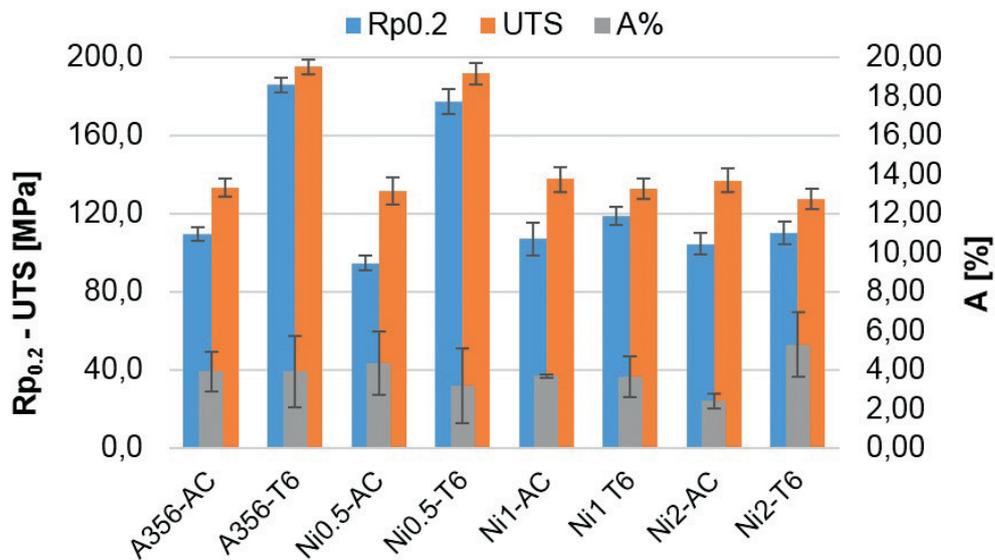
For each experimental condition, half of the castings were subjected to a T6 heat treatment. In order to prevent incipient melting of the eutectic regions, a two-step solutionising was carried out at 793 K (520 °C) for 2 h and then at 813 K (540 °C) for 2 h. The castings were then quenched in a water bath at 293 K (20 °C) and finally aged at 433 K (160 °C) for 6 h.

Tensile specimens with a round cross section (6 mm diameter and 40 mm gauge length) were machined and subsequently tested in accordance with the ISO 6892-2 specification using an MTS 880 universal testing machine (10 tons) equipped with a furnace chamber and a MTS Teststar control unit. The temperature in the furnace chamber was set at  $508 \pm 5$  K ( $235 \pm 5$  °C). All the as-cast and T6 heat-treated samples were kept at the pre-set temperature for 15 min before testing to ensure a homogeneous temperature. Tensile tests were carried out at a crosshead speed of 1 mm/min and with the applied load restricted to 40 kN. Six different experimental conditions were examined (Table 1), and at least five samples were tested in each condition.

Samples for microstructural investigations were cut from the tensile specimens, embedded in phenolic resin and prepared using standard grinding and polishing procedures. Microstructure and fracture analyses were performed using a LEICA MEF4M optical microscope (OM) and a ZEISS EVO 40 scanning electron microscope (SEM) equipped with an energy dispersive x-ray spectroscopy (EDS) detector.

## RESULTS AND DISCUSSION

The average values of the mechanical properties (yield strength  $R_{p0.2}$ , ultimate tensile strength UTS and percentage elongation A%) of the three Ni-containing alloys are shown in Figure 1. The addition of 0.5 wt% Ni slightly decreases  $R_{p0.2}$  in both as-cast and T6 conditions compared to the A356 base alloy. A further increase in Ni concentration up to 2 wt% has no influence on the high-temperature strength in the as-cast condition. This indicates that the rigid 3D network of Si and Ni-rich intermetallics failed to provide an enhancement of the high-temperature resistance [11]. Detailed investigations including X-ray tomography studies are currently in progress in order to understand the cause of this unexpected mechanical behaviour. Ni contents higher than 0.5 wt% yield a significant reduction in both  $R_{p0.2}$  and UTS of the T6 heat-treated alloys. It is also observed that the average values of the tensile properties of the Ni1-T6 and Ni2-T6 alloys are comparable to those of the corresponding as-cast alloys, implying that the beneficial effect of T6 heat treatment is neutralised to some extent by the early fracture of the brittle Ni-rich intermetallic phases [1]. No statistically significant difference in A% is observed between the base and the Ni-containing alloys in both as-cast and T6 conditions.

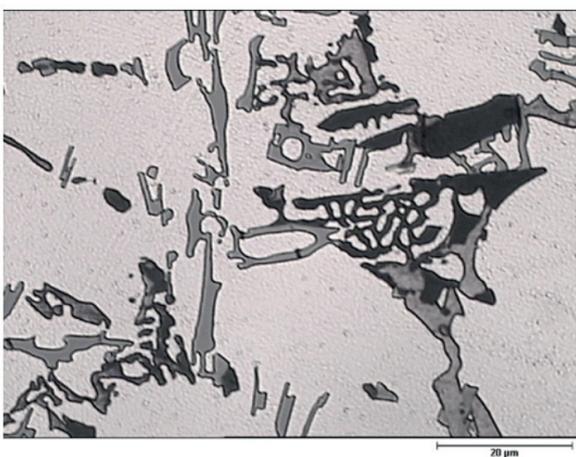


**Fig. 1** - High-temperature tensile properties.  
Tensile properties of the A356 base alloy (A356-AC/T6) [13] are also included.

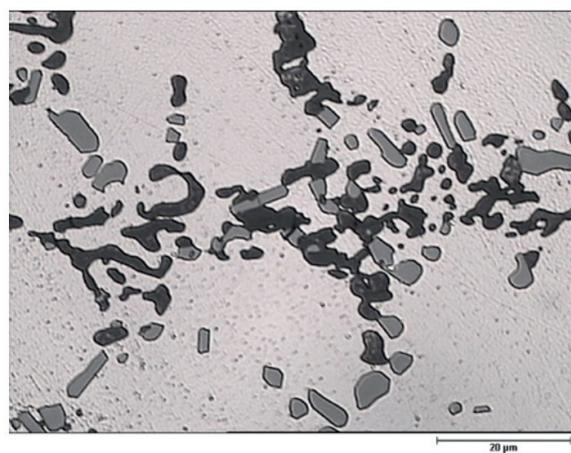
Representative microstructures of both as-cast and T6 samples are shown in Figure 2. The microstructure mainly consists of  $\alpha$ -Al dendrites, an Al-Si eutectic phase and Ni-bearing intermetallic compounds having polygonal or "Chinese-script" morphologies (dark grey after HF0.5 etching); coarse  $Mg_2Si$  and  $\pi-Al_8FeMg_3Si_6$  intermetallic phases are also detected in the as-cast samples. In contrast to the microstructural observations reported in [1],  $\beta-Al_5FeSi$  intermetallics were not found in the eutectic regions. Both eutectic Si particles and Ni-rich intermetallics undergo fragmentation and spheroidisation during solutionising and hence appear more round-shaped in the T6 samples (Figure 2b). In the Ni1-T6 and Ni2-T6 alloys, the increased amount of such inherently brittle Ni-bearing particles in the eutectic regions leads to a significant reduction in the high-temperature properties compared to the base alloy. As a result, these alloys exhibit a

mechanical behaviour remarkably different from that reported in [11] for an Al-7 wt% Si alloy solutionised at 768 K (495 °C) and overaged.

Figure 3a shows a backscattered electron (BSE) micrograph of a sample containing 0.5 wt% Ni in the T6 condition. Ni-rich phases (in light grey) were classified as  $Al_3Ni$  and  $Al_5FeNi$  by means of semi-quantitative EDS analysis. SEM observations of the fracture profiles (Figure 3b) and surfaces (not reported here) show several fractured Si and Ni-rich particles. Microcracks originated primarily from the latter constituents [1] can easily link one another propagating through the eutectic regions and finally forming the principal crack. The fracture path is irregular and areas with significant plastic deformation can be observed. Secondary cracks parallel to the main crack are also detected.

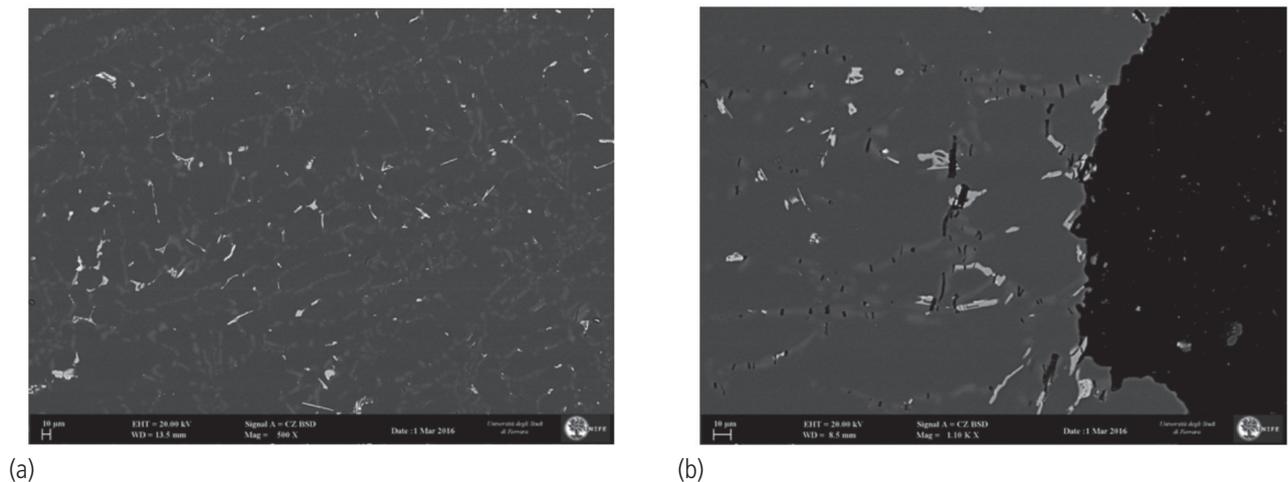


(a)



(b)

**Fig. 2** - High-magnification OM micrographs of a sample containing 2 wt% Ni in (a) as-cast and (b) T6 conditions.



**Fig. 3** - BSE micrographs showing (a) the microstructure and (b) the fracture profile of a sample containing 0.5 wt% Ni in the T6 condition. Aluminium dendrites are in dark grey, Si particles in the interdendritic regions appear in grey, whereas Ni-rich intermetallics are clearly visible in light grey.

## CONCLUSIONS

In this work, the effect of increasing Ni additions on the high-temperature strength of the commercial purity unmodified A356 aluminium foundry alloy was investigated. It was found that Ni contents higher than 0.5 wt% yield a significant reduction in both  $R_{p0.2}$  and UTS of the T6 heat-treated alloys. As a result, these mechanical properties become comparable with those of the corresponding as-cast alloys. The positive influence of the T6 heat treatment seems to be neutralised by the early fracture of the brittle Ni-rich intermetallics, which take the lead in the fracture process of the alloy.

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