

The effect of Ni and V trace elements on the mechanical properties of A356 aluminium foundry alloy in as-cast and T6 heat treated conditions

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ABSTRACT

In this study, the tensile properties of unmodified A356 alloys with trace additions of Ni or V were investigated. The nominal concentrations of these elements were set at 600 and 1000 ppm, respectively. Specimens obtained from sand and permanent mould casting in as-cast and T6 heat treated conditions were examined. It was found that the precipitation of Ni-rich intermetallics strongly influences the tensile properties of the sand cast A356 alloy in as-cast condition, leading to a reduction of both the yield strength ($R_{p0.2}$) and ultimate tensile strength (UTS) by 87% and 37%, respectively. Conversely, the V addition increased $R_{p0.2}$ and UTS by 42% and 25% due to a solid solution strengthening effect. After T6 heat treatment, the sand cast A356 alloys containing V exhibited slightly higher mechanical properties as compared to the A356 reference alloy ($\approx 18\%$), whereas the detrimental effect of Ni was eliminated. The cooling rate became the main parameter influencing the mechanical properties of permanent mould cast alloys: no significant differences in mechanical properties were observed between the reference alloy and Ni- or V-containing alloys in both as-cast and T6 conditions.

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1. Introduction

Al–Si foundry alloys are widely used in the automotive industry owing to their good castability, high strength-to-weight ratio, corrosion resistance and ease of recycling. Good mechanical properties at room temperature can be obtained by a heat treatment involving solutionising and subsequent age hardening. Depending on the chemical composition of the alloy, several phases, such as Mg_2Si , precipitate in the α -Al matrix. This increases the alloys strength significantly, because these small scale precipitates impose a barrier for the motion of dislocations [1].

Aluminium producers that are currently focusing primarily on the control of dissolved hydrogen, Na content and inclusion removal are now facing increasing Ni and V concentrations originating from the petroleum coke used for manufacturing of anodes for the Al electrolysis. In the upcoming years, the levels of Ni and V in the coke are expected to rise to 420 and 1080 ppm,

respectively [2]. Estimates show that up to 50% of these elements partition into the primary aluminium during the electrolytic reduction of alumina. Since there is yet no cost efficient method available for removal of these elements, the concentration of Ni and V will also increase in the downstream products [3]. Thus it is important to establish whether these concentrations have a beneficial or detrimental effect on the microstructural features, and consequently on mechanical, corrosion and manufacturing properties.

Recent literature focuses primarily on Ni and V as alloying elements. It was shown that Ni serves as iron neutraliser. It transforms the brittle plate-like β - Al_5FeSi intermetallics into the elongated Al_3FeNi phase in a peritectic reaction [4,5]. However, the Al_3FeNi phase is also brittle and contributes to the nucleation of fatigue cracks [6]. Owing to the well-established low thermal and metallurgical stability of Al–Si alloys [7,8], several authors have recently investigated complex hypoeutectic and near-eutectic alloys with various additions of Ni, with the aim of developing high strength alloys for high temperature applications (i.e. up to 250 °C) [9–13]. It was generally observed that Ni stabilises the mechanical properties of Al–Si-based alloys at elevated temperatures. Improved mechanical properties at high temperature were

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obtained by Heusler et al. [9]. They presented a new alloy for engine applications based on the Al–Si–Mg–Cu–Fe–Ni system with increased fatigue properties (+20%) and tensile strength. This increase was attributed to the presence of Ni-bearing intermetallic compounds. Asghar et al. [10] reported significant elevated-temperature strength in a Al–12SiNi alloy. The addition of 1.2 wt% Ni led to the formation of an interconnected hybrid reinforcement consisting of eutectic Si and Ni- and Fe-containing aluminides. Li et al. [11] found that the stable δ -Al₃CuNi phase possesses the most efficient contribution to high temperature strength compared to the other Ni-containing phases due to its strip-like interconnected morphology in Al–Si piston alloys. This was confirmed by Farkoosh et al. [12]. They observed that this phase contributes most significantly to the T7 hardness of an Al–7Si–0.5Cu–0.35Mg–0.1Fe–XNi alloy. Peak hardness values were achieved for a Ni: Cu wt% ratio of 1.5. In addition, thermally stable Ni intermetallics were credited for the increase of the yield strength at 300 °C [13]. However, the Al₃FeNi phase is very brittle even at elevated temperatures and its rupture at the early stage of creep deformation can reduce the creep resistance of the alloy.

The addition of solutes such as V that form trialuminides in a peritectic reaction is known to be an effective method to introduce active heterogeneous nucleant particles promoting the grain refinement of Al alloys [14]. Recently, Kasprzak et al. [15] developed a high temperature alloy based on a A356 with the addition of Ti, V and Zr (nominal V concentration of 0.2 wt%). They indicated that stable Al–Si–Zr–Ti nanoprecipitates in the α -Al matrix are the cause of superior mechanical properties at high temperature compared to the reference alloy (+34% yield strength, +37% UTS). However, the role of V remained unclear even though the concentration was increased to 0.2 wt%. Kasprzak et al. did not observe V-based intermetallic compounds in the microstructure of their alloys.

Only few investigations deal with the effects of Ni and V as trace impurity elements in hypoeutectic Al–Si alloys. Currently, they contain low levels of Ni and V, in the range of 20–30 ppm and 100–110 ppm each [3,16]. In a recent publication Zhu et al. showed that the addition of trace element Ni of up to 0.02 wt% does not influence the as-cast microstructure of A356 alloy, whereas an unidentified phase with high Ni content formed when the Ni concentration was increased to 0.05 wt% [17]. Microstructural observations reported by Ludwig et al. [18] on both high purity and commercial purity Al–7 wt% Si foundry alloys revealed that Ni in concentrations exceeding 300 ppm forms the Al₃Ni phase in the high purity alloy. Both Al₃Ni and Al₃FeNi intermetallic phases precipitated in the commercial purity alloy. This study also indicated that V in concentrations up to 0.06 wt% remains in solid solution or is dissolved in ternary Al–Fe–Si phases. Since the solid solubility of V in Al is approximately 0.1 wt% [19], most of the V will remain in the α -Al matrix. Beyond this concentration, V and Si will precipitate as pre-eutectic Si₂V crystals with a distinct polyhedral morphology [16,20].

At present, only the EN 1676–2010 specification defines an upper concentration limit for V of 0.03 wt% for EN-AB 42100 aluminium foundry alloys, which corresponds to A356 alloys, whereas there exists no information about the maximal tolerable Ni concentration in this alloy system. Therefore, the aim of the present work is to investigate the effect of the trace elements Ni and V on the mechanical properties of as-cast and T6 heat-treated A356 aluminium foundry alloys in two commercially important casting processes: (i) sand and (ii) permanent mould casting. Microstructural and fractographic analyses were performed to investigate the microstructural features involved in the fracture process. This study also intends to give an indication of the tolerable levels of Ni and V, in order to establish if current alloy specifications can be adjusted to accommodate higher Ni and V

concentrations while the alloy maintains similar mechanical properties as the A356 reference alloy.

2. Materials and methods

A commercial A356 aluminium alloy was used as base alloy in the present study. The as-received alloy ingots were melted in charges of 16 kg in a boron-nitride coated clay-graphite crucible. Trace elements were added in the form of Al–10 wt% Ni and Al–10 wt% V master alloys according to the targeted nominal concentrations of 600 and 1000 ppm of Ni and V, respectively. In order to avoid any masking effects or interactions with additional elements, neither Sr nor Na was added as modifier agents. The melting temperature was monitored with the Alspek-H probe and was kept constant at 740 °C $\pm$ 5 °C. Samples from the three different melts were taken throughout the casting trials and were analysed by optical emission spectroscopy (OES). The chemical composition of the reference and the Ni- and V-containing alloys is given in Table 1.

The hydrogen content in the melts was measured in-situ with the Alspek-H probe. Melts were degassed with argon gas in order to reach a hydrogen concentration of 0.08 ml H₂/100 g Al. This impeded porosity formation in the samples. As a direct consequence, this defect was not regarded as a parameter influencing the tensile properties.

The alloys were then poured in both sand and steel moulds. Sand castings were produced using an upgraded version of the tensile test bar design proposed by Dispinar and Campbell [21]. In this new casting design (Fig. 1), the shape of the bars varied from cylindrical to tapered, with diameters increasing gradually from 15 mm (bottom) to 20 mm (top). Permanent mould castings were obtained by pouring the molten alloys into a L-shaped preheated steel mould (Fig. 2), manufactured according to the UNI 3039 specification. The temperature of the die was kept at 300 °C during

Table 1
Chemical composition (wt%) of A356 reference alloy and Ni/V-containing alloys as measured by OES.

Alloy	Addition (ppm)	Si	Fe	Mg	Ni	V	Al
A356		7.054	0.092	0.355	0.003	0.007	bal.
A356+Ni	600	6.902	0.087	0.344	0.061	0.007	bal.
A356+V	1000	6.992	0.094	0.349	0.003	0.108	bal.

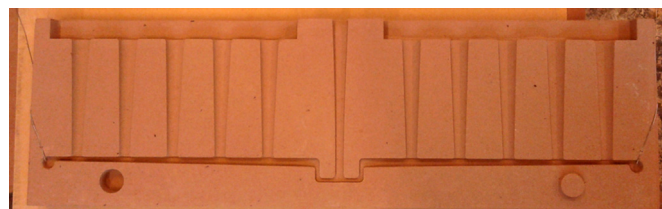


Fig. 1. Design of the sand mould. Raw tensile test bars are tapered, with diameters increasing gradually from 15 mm (bottom) to 20 mm (top).



Fig. 2. Design of the L-shaped permanent mould.

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