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Mechanical properties and thermal stability of Al–Fe–Ni alloys prepared by centrifugal atomisation and hot extrusion

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ABSTRACT

In this work, Al–12Fe and Al–7Fe–5Ni (wt%) alloys prepared by a novel technique including centrifugal atomisation and hot extrusion were studied. The microstructures were investigated using light microscopy, electron scanning microscopy, transmission electron microscopy and X-ray diffraction. The mechanical properties were determined by Vickers hardness measurements and compressive stress–strain tests. To study the thermal stability, the mechanical properties were also measured after 100 h of annealing at 300 °C and 400 °C. In addition, creep tests at a stress of 120 MPa and a temperature of 300 °C were performed. The investigated materials were composed of fine-grained α-Al and intermetallic phases identified as $Al_{13}Fe_4$ and Al_9FeNi. The Vickers hardness and compressive yield strength were 68 HV5 and 183 MPa, respectively, for the Al–12Fe alloy and 73 HV5 and 226 MPa, respectively, for the Al–7Fe–5Ni alloy. After long-term annealing, the change in the mechanical properties was negligible, indicating the excellent thermal stability of both materials. The creep tests confirmed the highest thermal stability of the Al–7Fe–5Ni alloy with a total compressive creep strain of 15%. The “thermally stable” casting Al–12Si–1Cu–1Mg–1Ni alloy treated by the T6 regime was used as a reference material. The casting alloy exhibited sufficient mechanical properties (hardness and compressive yield strength) at room temperature. However, annealing remarkably softened and reduced its compressive yield strength to almost 50% of the initial values. Additionally, the total creep strain of the casting reference material was almost three times higher than that of the Al–7Fe–5Ni alloy. It has been proven that centrifugally atomised materials quickly compacted via hot extrusion can compete or even exceed the properties of common casting aluminium alloys that are used in automotive industry.

1. Introduction

Aluminium-based alloys are one of several materials that have attracted much attention in the last century. They are prospective materials with a good weight-to-strength ratio and corrosion resistance. Excellent thermal stability can be achieved if appropriate amounts of transition metals (TMs) are added [1–3]. The mechanical properties of the produced aluminium alloys are closely correlated to the content of the alloying elements [4–6], as well as to the processing technology used [7–9]. However, elements such as iron have strongly limited solubility in solid aluminium; therefore, a relatively coarse and brittle intermetallic phase may form. The mechanical properties of these materials are deteriorated by the presence of these structural components, which serve as sites of crack nucleation and growth. Therefore, a solution to this problem can be found in the production of these materials by powder metallurgy (PM) techniques. PM has attracted a great deal of attention in modern metallurgy in recent years. Aluminium alloys produced by PM are of interest mainly for the automotive and aerospace industries [10]. In general, powder production techniques can be divided into several methods, including mechanical alloying and techniques focused on rapid solidification (RS).

In the past, iron has been considered less as a beneficial alloying element and more as an undesirable impurity. However, iron exhibits great potential for reinforcement in aluminium alloys due to the formation of relatively thermally stable intermetallic phases. The thermal stability can be attributed to the significantly lower diffusion coefficient of iron in solid aluminium compared to that of other typical alloying elements (silicon, copper, and magnesium) found in commercial engineering aluminium alloys. However, to achieve a high thermal stability of Al–Fe alloys, the concentration of Fe must be sufficiently high. As indicated previously, materials prepared by conventional ingot or casting metallurgy contain large and brittle intermetallic phases such as the $Al_{13}Fe_4$ (θ) phase, which deteriorates the mechanical properties [11]. Therefore, there is a necessity to reduce the size and volume fraction of the brittle intermetallic phases containing iron. RS techniques have been widely used for this purpose.

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One of the first reports on rapid solidification and its positive effect on the resulting mechanical properties came from Duwez and coworkers in the early 1960s [12]. They observed that materials prepared under certain conditions, including especially rapid heat extraction from molten metal, exhibit extraordinary properties. Increased solid solubility and the presence of metastable crystalline or even amorphous phases opened a way to process materials with increased amounts of alloying elements far exceeding the total solubility in the solid matrix. Since then, various RS techniques including centrifugal atomisation (CA) have been developed. Cooling rates in the range of 10^4–10^8 $K \cdot s^{-1}$ are typical of processes in a rapid solidification regime [13–16]. Several works reported that the cooling capability of the CA technique strongly depends on the setting and arrangement of the experimental apparatus and can typically reach cooling rates in the range of 10^4–10^7 $K \cdot s^{-1}$ [17–20]. Nevertheless, such a rapid heat transfer from the molten metal allows the production of new materials that exhibit superior properties. Rapidly solidified products (powders, milled ribbons) are typically compacted via hot extrusion, hot isostatic pressing (HIP) or uniaxial pressing. The most widely used technique for compaction is hot extrusion, which is characterised by relatively high temperatures and short times, which prevent microstructural coarsening.

Al–Fe-based alloys have been the subject of interest for several years because of their good mechanical properties at elevated temperatures [11]. There are several reports showing that newly developed Al–Fe-based alloys prepared via RS and compaction can compete with the titanium alloys used for aerospace applications up to 573 K [11,14,21]. It has also been shown that the addition of Ni can lead to the formation of fine dispersoids of Al_3Fe, Al_6Fe or Al_3Ni phases, improving the high-temperature mechanical strength, increasing the modulus of elasticity and lowering the coefficient of thermal expansion [22]. Thus, the present study focuses on Al–Fe and Al–Fe–Ni alloys prepared by PM. The RS powders were prepared by the CA technique, which is relatively simple, inexpensive and therefore suitable for the large-scale production of powders. However, to our knowledge, CA has not yet been used for the preparation of Al–Fe–Ni alloys.

2. Experimental details

The PM materials with nominal chemical compositions of Al–12Fe and Al–7Fe–5Ni (wt%) investigated in this work were prepared by vacuum induction melting of appropriate amounts of pure Al, Ni and Al–12Fe (wt%) master alloys under a protective argon atmosphere. After sufficient homogenisation, the melt was poured into a brass mould, forming a slowly solidified cylindrical ingot that measured 20 mm in diameter and 150 mm in length. The prepared ingots were consequently remelted under argon to prevent oxidation and ejected through the graphite nozzle with 1 mm in diameter onto a high-speed rotating graphite disc (rotation speed of 30,000 rpm), forming rapidly solidified powders (Fig. 1). The chemical compositions of all the investigated alloys were confirmed by X-ray fluorescence spectrometry (XRF, ARL 9400 XP) and are listed in Table 1. The Al–12Si–1Cu–1Mg–1Ni (wt%) alloy, which is commonly considered to be thermally stable and therefore mostly used for engine part manufacturing [23], was used as a reference material. It was obtained in the form of an ingot from an external supplier and was heat-treated by the T6 regime, consisting of solution annealing (510 °C/5 h), water quenching and artificial aging (230 °C/6 h) [24].

It should be noted that the powders prepared via CA are flake-like particles (Fig. 2) that are much easier to process into compact products than the ribbons prepared by melt-spinning technology.

RS powders were sieved to obtain a powder with a particle size of 0.1–2 mm and a thickness of approximately 50 μm. Afterwards, this powder fraction was pre-compacted by a pressing mould made from tool steel into a cylindrical specimen 19 mm in diameter and 25 mm in height by a pressure of 210 MPa, providing sufficient cohesion for further steps. The pre-compacted semi-product was then preheated at 550 °C for 10 min and subsequently extruded at an extrusion ratio of 10:1 and a deformation rate of 2.5 mm/min to produce rods 6 mm in diameter.

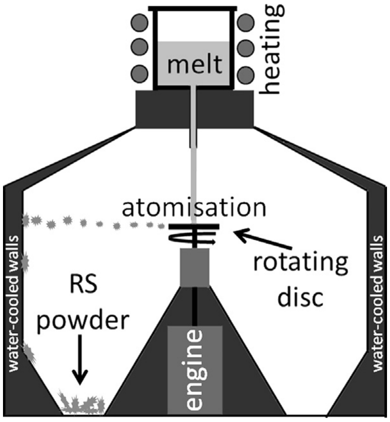

Fig. 1. Schematic drawing of the centrifugal atomisation apparatus producing rapidly solidified (RS) powders.

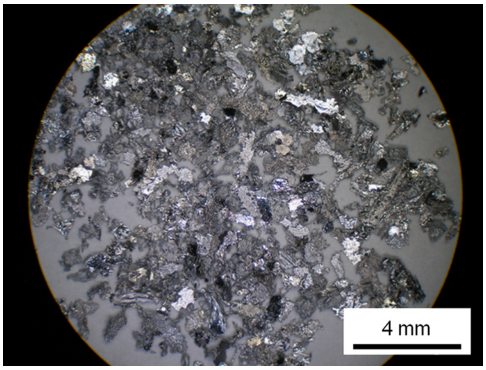

Fig. 2. Flake-like powder particles prepared by centrifugal atomisation (CA).

Table 1
Chemical compositions (wt%) of the investigated alloys.

Material (preparation)	Element (wt%)									
	Ca	Cr	Cu	Fe	Mg	Mn	Ni	Si	Ti	Al
Al–12Fe (PM)	–	–	–	11.9	–	0.1	–	0.2	–	Bal.
Al–7Fe–5Ni (PM)	–	–	–	7.2	–	–	4.7	0.2	–	Bal.
Al–12Si–1Cu–1Mg–1Ni (casting, T6 heat treatment)	0.1	0.1	1.2	0.2	1.0	0.2	0.9	11.8	0.1	Bal.