Evaluating extrudability of particle-reinforced 2124-Al MMCs and MMNCs within the warm working temperature range (170-280°C)

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Abstract. This work evaluates the warm temperature extrudability of 2124-Al alloy metal matrix composites (MMCs) and metal matrix nano composites (MMNCs) produced by powder metallurgy. Green and sintered compacts were produced by mixing and blending 2124-Al alloy powder with 5 and 10 vol. % Al2O3 or 10 and 15 vol. % SiC powders in a high energy ball mill, followed by ambient temperature compaction and sintering at 490°C for 1 hr. An extrusion die was designed to reduce the diameter of the compacts by 30% from 8 mm to approximately 5.6 mm, and the die set was manufactured from H13 hot work tool steel. The die and samples were heated and soaked for 20 minutes, using a high temperature furnace, before extrusion in an Instron® press. Extrusion parameters, such as temperature and speed, were informed by uniaxial compression tests performed on a Gleeble 3500® together with results from Abaqus finite element modelling. The extrusion temperature was 280°C and the speed was 7 mm/s. Extrudability of the unreinforced 2124-Al was good, while the 5 vol. % Al2O3 reinforced MMNC and both SiC reinforced MMCs had poorer warm temperature extrudability. The composites were more difficult to extrude than the unreinforced alloy because they have higher resistance to deformation due to the hard and stiff reinforcing particles which do not deform easily. Also, this was attributed to a lack of lubrication during extrusion, which could have increased the friction and resistance to deformation, reducing material flow. Based on microstructural analysis, extrusion showed potential to improve distribution of SiC particles in 2124-Al grains. However, it seems that more deformation is required.

1. Introduction

Metal matrix composites (MMCs) are formed when an intermetallic compound, ceramic, metal or metallic alloy is embedded in a continuous metallic phase [1][2]. The metallic phase takes on the role of the ductile matrix and the phase embedded in it is the reinforcement [3]. The matrix protects the reinforcement and keeps it in an established position, while the reinforcement enhances the
mechanical and physical properties of the matrix [4], such as hardness, strength and thermal stability [5].

MMCs may be continuously reinforced with fibres, or discontinuously reinforced by dispersed particles or whiskers with higher hardness in the matrix [3][6]. In MMCs, the size of the reinforcement phase is in the micron-size range, \textit{i.e.} >100 nm [7]. When the size of the reinforcement is reduced to the nano-size range, \textit{i.e.} 1-100 nm, the composite is referred to as a metal matrix nano composite or MMNC [7][8].

In literature, there is a large body of work dedicated to the development of metal matrix composites (MMCs) and metal matrix nano composites (MMNCs). Achieving a uniform distribution of reinforcing particles in the matrix material continues to be the biggest challenge when fabricating discontinuously reinforced MMCs and MMNCs [9]. It has been reported that a deformation process, such as extrusion, can improve the distribution of the reinforcement in the matrix and strengthen the interfacial bonds between reinforcing particles and the matrix, ultimately enhancing mechanical properties such as hardness and strength[10].

Extrusion is a plastic deformation process where the cross-sectional area of a billet is reduced by applying a compressive force and forcing the billet to flow through a die hole with a smaller diameter [11]. The extrusion temperature is an important parameter because it influences other process variables [12]. When the extrusion temperature is increased, plastic flow in the billet is improved due to a decrease in flow stress, so the required load is lowered and deformation becomes easier [8][12]. This is the main advantage with extruding at high temperatures, referred to as hot extrusion. However, in some studies, high temperatures have been associated with defects such as surface cracks as well as poor surface finish and poor dimensional accuracy. Cold extrusion is done at ambient temperature. While the challenges experienced at higher temperatures are eliminated with cold extrusion, it has its own shortcomings [13], including high stresses due to limited plastic flow and the requirement for high capacity presses which may shorten the service life of the die set [14]. It is evident that there are shortcomings with both hot and cold extrusion, which has created an interest in intermediate warm working temperatures.

Warm working, at temperatures between 30 and 60\% of the matrix material melting point, has been shown to have some advantages over both cold and hot working [15][16]. According to [17], there has been an increase in the use of warm forming technologies in the past twenty years. However, there is not much literature on the effect of warm working on deformation and properties of materials, particularly on warm temperature extrudability.

Extrudability was defined by [18] as a metal’s ability to withstand deformation and indicates the ease with which the metal can be deformed. This work evaluates the warm temperature (170-280°C) extrudability of 2124-Al MMCs and MMNCs produced by powder blending in a high energy ball mill. The main focus is on the effect of warm temperature extrusion on the deformation and microstructures of these composites, as well as the distribution of the reinforcing particles in the aluminium matrix.

2. Experimental procedure

Laboratory scale extrusion experiments were done on powder metallurgically produced compacts. Green and sintered compacts were made by mixing and blending 2124-Al alloy powder with Al2O3 (5 and 10 vol. \%) or SiC (10 and 15 vol. \%) powders in a Simoloyer CM-01® 2L horizontal high energy ball mill, followed by ambient temperature compaction and sintering at 490°C for 1 hr. Uniaxial compression tests showed that a temperature of 280°C and a strain rate of 5 s\(^{-1}\) produced uniaxially compressed samples with the best integrity [19]. Results from these uniaxial compression tests were used as input data for finite element analysis (FEA) using Abaqus. According to the FEA, a strain rate of 5 s\(^{-1}\) is equivalent to an extrusion speed of 7 mm.s\(^{-1}\) which was then used for the laboratory scale extrusion experiments. An extrusion die was designed to reduce the diameter of the compacts by 30\% from 8 mm to approximately 5.6 mm, and the die set was manufactured from H13 hot work tool steel. The die and samples were heated to 280°C and soaked for 20 minutes, using a high temperature furnace, before extrusion in an Instron® press. The Instron® press was connected to a computer and the
Bluehill® (version 2) software was used to study and depict the materials’ response during extrusion. All the samples had an initial diameter of 8 mm which was inserted into the Bluehill® software prior to extrusion. The movement of the samples in the die, while being extruded as well as the applied load were monitored. The movement of the samples in the die, as a result of the applied load, gave an indication of compressive extension (mm) while the software used the applied load and change in sample diameter to calculate compressive stress. The materials’ response was depicted using curves of compressive extension (mm) against compressive stress (MPa). Metallography using a Leica DM15000M® optical microscope and Jeol-6510® scanning electron microscope (SEM) showed the microstructural evolution of the unreinforced 2124-Al alloy, SiC reinforced MMCs and Al₂O₃ reinforced MMNCs during each process step.

3. Results and discussion

3.1 Microstructural evolution (blending, compaction & sintering)

Micrographs showing the microstructural evolution in the unreinforced 2124-Al and composite materials are presented in Figures 1, 2 and 3. Figure 1a shows that the particles of the 2124-Al alloy powder were spherical and, with the exception of a few agglomerated smaller particles, appear to be of similar size. The microstructure of the unreinforced 2124-Al alloy green compact was inconsistent from the surface to the core. Figures 1b and 1c show that better consolidation was achieved at the surface of the 2124-Al green compact than at the core. Figure 1c shows that there was a lot of porosity (shown by darker areas) at the core. This inconsistency in consolidation indicates that there was a density variation in the 2124-Al green compacts as a result of friction effects during compaction. Pressure gradients, caused by friction between the powder and the die walls, lead to non-uniform density distribution in green compacts [20]. The frictional force opposes the applied force and decreases the amount of pressure transmitted to the powder for consolidation [21]. The mid-height of the green compact is therefore exposed to less pressure which would explain the poorer consolidation achieved at the core when compared to the surface of the green compact.

A more uniform distribution of reinforcing particles on the aluminium alloy powder particles was achieved in the Al₂O₃ reinforced MMNCs (Figure 2a) than the SiC reinforced MMCs (Figure 3a). Figures 2b and 3b show that, in the green compacts, reinforcing particles agglomerated at 2124-Al grain boundaries which was attributed to limited plastic flow during cold compaction. So, during cold compaction, there is no mechanism for reinforcing particles at grain boundaries to migrate to the inside of the grains.

Cold compaction of 2124-Al with 10 vol. % Al₂O₃ powder was unsuccessful as the green compacts fractured into nearly horizontal slices. This fracturing was attributed to poor bonding and plastic flow due to the higher density of Al₂O₃ particles on the surface of the 2124-Al alloy powder particles. This result highlighted the need to explore other consolidation techniques, such as spark plasma sintering (SPS), for this MMNC.

It can also be observed that the white eutectic phase inside the 2124-Al alloy grains spheroidised due to incomplete eutectic dissolution (Figures 1d, 2c and 3c). The implication of this incomplete dissolution is that there would be fewer precipitates formed if the materials were subjected to an ageing heat treatment, so the hardness in the aged condition would most likely not differ much from the unaged alloy.
Figure 1. Micrographs showing microstructural evolution in unreinforced 2124-Al from (a) as-received powder (scale bar=100µm) to (b, c) compaction (scale bar=250µm) and (c) sintering (scale bar=50µm).

Figure 2. Micrographs showing microstructural evolution in Al₂O₃ reinforced MMNCs from (a) blending (scale bar=50µm), (b) compaction (scale bar=2µm) and (c) sintering (scale bar=50µm).

Figure 3. Micrographs showing microstructural evolution in SiC reinforced MMCs from (a) blending (scale bar=50µm), (b) compaction (scale bar=50µm) and (c) sintering 9scale bar=50µm).

3.2 Extrusion
Figure 4 shows curves of compressive extension (mm) as a function of compressive stress (MPa) depicting the materials’ response during extrusion. Compressive extension refers to the movement of the samples during extrusion as a result of the load being applied. The aim of the extrusion process was to apply a compressive force to the samples (d=8mm) and force them through a die hole of smaller diameter (d=5.6mm) [11]. It can be observed that the unreinforced 2124-Al alloy extruded well and plastically deformed as the dark blue curve labelled 1 in Figure 4 shows that this sample had the highest compressive extension (approximately 15mm). The sudden increase in stress for the Al alloy (the dark blue curve labelled 1 in Figure 4) shows that there was some effect of a lack of lubrication where friction between the die and sample became too high. This increased the resistance to deformation and therefore increased the compressive stress. The materials reinforced with 5% Al₂O₃, 10% SiC and 15% SiC, had very similar maximum compressive stresses at ~900 MPa. The curve shapes of the composites also show that there was limited plastic deformation before the maximum compressive stress was reached. The shape of the curves for the SiC reinforced samples in Figure 4 (curve 3: 10%SiC and curve 4: 15%SiC) are similar which suggests that the materials behaved in a similar manner during extrusion, with total compressive extensions of only 2.7 mm and 2 mm respectively; regardless of the difference in vol. % of SiC (10 vs. 15%). However, curve 2 shows that the composite reinforced with Al₂O₃ had a slightly higher compressive extension (approximately 8.3mm); implying that it had a lower resistance to deformation.
Figure 4. Compressive extension (mm) vs. compressive stress (MPa) for (1) unreinforced 2124-Al (2) 2124-Al with 5% Al$_2$O$_3$ (3) 2124-Al with 10% SiC and (4) 2124-Al with 15% SiC during extrusion.

The extruded samples were sectioned along their axes of symmetry, in the extrusion direction, and analysed. Figure 5a shows that in the unreinforced 2124-Al sample, the grains deformed and changed shape. There seems to be good bonding between the 2124-Al alloy grains but there were also many micro voids on the grain boundaries. It was inferred that these micro voids formed due to particle debonding during deformation. Some deformation was achieved in the 2124-Al with 5% Al$_2$O$_3$ MMNC since the 2124-Al grains changed shape during extrusion (Figure 5b). However, the Al$_2$O$_3$ particles concentrated on the 2124-Al alloy grain boundaries could have limited plastic flow by limiting movement of the 2124-Al grains at the grain boundaries [24].

In the 2124-Al with 10% SiC extruded sample, deformation by elongation of the matrix grains during extrusion can be seen (Figure 5c). This micrograph shows that the SiC particles lie in narrow bands in the extrusion direction. There are some areas where the matrix grains have bonded and there are a few SiC particles distributed inside the deformed grains. Figure 5c illustrates that extrusion could potentially improve matrix grain deformation and distribution of SiC particles inside the 2124-Al grains, however it seems that higher deformation (i.e. higher reduction in area) has to be achieved.

Figure 5d shows that the grains in the 2124-Al with 15% SiC sample deformed during extrusion. The higher vol. % of SiC led to more SiC particles concentrated on grain boundaries. While the 2124-Al grains elongated due to deformation, there were very few SiC particles dispersed in the deformed regions. It was deduced that the deformation was restricted to some extent by the high amount of SiC on grain boundaries. There was more resistance to the applied force with 15% SiC than with 10% SiC.
5. The extrudability of particle-reinforced 2124-Al MMCs and MMNCs within the warm working temperature range (170-280°C) was evaluated. The following conclusions were made:

1. Extrudability of unreinforced 2124-Al was good while the Al2O3 reinforced MMNC and SiC reinforced MMCs had poorer warm temperature extrudability due to higher resistance to deformation (owing to the absence of reinforcing particles) and possibly lack of lubrication.

2. Extrusion showed potential to improve the distribution of SiC particles in the 2124-Al reinforced with 10% SiC composite; however, it seems that more deformation is required.

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