



Review

Effect of extrusion ratio on the wear behaviour of Al–Si and Al–Mg alloys

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ABSTRACT

In this study, the wear behaviour of hot extruded Al–Si and Al–Mg alloys was investigated under dry conditions. Die cast Al–Mg alloy containing 1.7% Mg and Al–Si alloy containing 3.3% Si were extruded at 1.6 and 2 ratios. Mechanical and microstructural characterisations of the extruded alloys were carried out through optical microscopy, hardness measurements and tensile testing. Wear tests were carried out on a pin-on-disc type wear device and the worn surfaces were examined under a scanning electron microscope (SEM). The wear test results revealed that the extrusion ratio had an influence on the wear rate and that the samples extruded at a ratio of 1.6 had a lower wear resistance than the ones extruded at a ratio of 2.

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1. Introduction

There is a growing interest in the wear behaviour of aluminium alloys as more and more of these alloys, both in type and quantity, are being used in different areas of technology [1,2]. Of the aluminium-based alloys, aluminium–silicon alloys are probably the most investigated ones for their tribological behaviour [3–8]. In recent years, aluminium–magnesium alloys have been very attractive in the applications for the automotive, railway and aerospace industries from an ecological point of view. One of the technical attractions for the widespread use of magnesium alloys in structural applications is the improvement of creep strength at elevated temperatures [9–16]. Aluminium–silicon alloys have drawn a great deal of attention from the automotive industry, device and machine manufacturing, construction and architecture since they have very good mechanical and physical properties, good formability, high

strength, superior corrosion resistance, good wear features and weldability [17,18]. Various researchers have long been studying the shaping of aluminium alloys using extrusion.

The hydraulic extrusion press was invented in 1810 by an Englishman called S. Bramah. His press was designed for the extrusion of lead. The first successful application of the process was on alloys with high melting points, applied by a German called A. Dick, in the 1890s [19,20]. Extrusion is a deformation process used to produce long, straight, semi-finished metal products such as bars, solid and hollow sections, tubes, wires and strips. The principle of the process is that; under high load, a billet is squeezed from a closed container through a die to give a reduction in size [19]. Cross sections of varying complexity can be extruded at a room temperature, or at high temperatures, depending on the dies, the alloy and the method used.

Extrusion ratio (ER) [20] of a die is

$$E_R = \frac{A_c}{n \times (A_E)}$$

where “n” is the number of symmetrical parts, “A_c” is the cross-sectional area of the billet to be extruded and “A_E” is the cross

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Table 1

Extrusion processing conditions for extrusion ratios of 1.6 and 2.

Parameter	Ext. ratio 1.6	Ext. ratio 2
Mat. input temp.	350 ± 5 °C	350 ± 5 °C
Die input temp.	300 ± 5 °C	300 ± 5 °C
Sample input dia.	20 mm	20 mm
Sample output dia.	16 mm	14 mm
Sample input leng.	50 mm	50 mm
Sample output leng.	70 mm	100 mm
Sample output temp.	128 °C	135 °C
Sample exit time	50 s	55 s
Press pressure	2.5–3 MPa	2.5–3 MPa

sectional area of the extruded-product. In this study only one part at a time is extruded, therefore $n = 1$, A_c is constant, and accordingly when the extrusion ratio of a profile is low, A_E is high.

The extrusion ratio of a shape is a direct indicator of the mechanical energy used while obtaining the shape with extrusion.

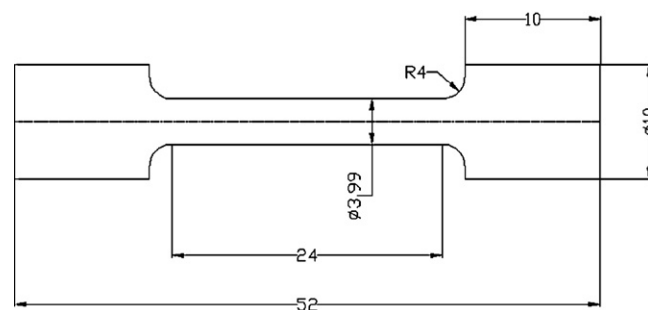
It is clear from the published work that there are various studies regarding the effects of the extrusion ratio on the mechanical and wear behaviour of aluminium alloys [21–25]. In the previous studies, experiments were carried out for extrusion ratios reaching up to 40; their results showed that after the extrusion procedure, a 70–80% deformation occurred [26–28]. The structure of aluminium subjected to low ratios of extrusion is similar to that of the cast aluminium (coarse-grained). This structure is mechanically weak. Hence, it is likely that mechanical and physical properties of the products subjected to extrusion at the ratios below 10 may vary from the values reported in the literature [20]. In addition, some investigations show that a higher extrusion ratio (≥ 39) is more effective than a lower one (≤ 24) to refine the grains for Mg alloys [25]. Milenin et al. [29] conducted studies with an extrusion ratio of 5. After analysing the results of the extruded sample, the procedure was regarded as successful. This is the lowest extrusion ratio in the literature.

In this study, Mg and Si in a similar amount to the Si and Mg contents of commercial aluminium alloys were added to form a binary alloy and the effects of the alloying elements were analysed. Al–Si and Al–Mg alloys were produced using die casting. The produced samples were extruded using various extrusion ratios that were lower than 5, 1.6 and 2. Standard characterisation procedures were applied to the extruded samples and microstructure images were taken. Microhardness measurements and the tensile test were conducted on the samples.

2. Experimental procedures

In this study, Al–Mg alloys, with a chemical composition of 1.7% Mg, 0.6% Si, 0.3% and Al–Si alloys with a chemical composition of 3.3% Si, 0.41% Mg, 0.585% were produced using die casting method in the dimensions of $\varnothing 20 \text{ mm} \times 150 \text{ mm}$. The casting temperature of the analysed alloys was determined as 720 °C, using a chromel–alumel thermocouple. The metal mould was pre-heated at 220 °C, prior to the casting procedure. After the casting process, Al–Mg alloys were homogenised for an hour at 400 °C, while Al–Si alloys were homogenised for an hour at 500 °C, in order to avoid segregations. The homogenised samples were cut to $\varnothing 20 \text{ mm} \times 50 \text{ mm}$ dimensions for extrusion. The extrusion was carried out under the experimental conditions indicated in Table 1, with the help of a 50-ton hydraulic press, at two different ratios (1.6 and 2). While the input temperature of the materials was 350 °C, the die input temperature was 300 °C and input diameter was 20 mm for all the samples. Pre-prepared dies with 2° and 3° draft angles were used.

The extruded samples were subjected to microstructural characterisation, grain size measurements, microhardness measurements, tensile test and wear tests. Standard procedures were used for microstructural characterisation. Optical microscopy analysis and scanning electron microscopy (SEM) analysis were conducted at this stage. The samples were then cold mounted using a PRESI mounting kit in order to conduct metallographic examinations. All samples were ground using a PRESI MECAPOL P262 device with 180, 240, 320, 600 and 1200 grits emery papers. Polishing was carried out using a 3 μm and 1 μm diamond solution. After being polished with 1 μm , the samples were cleaned using pure alcohol and etched for 10 s with 2.5 ml HNO_3 , 1.5 ml HCl , 1 ml HF , 95 ml H_2O . Microstructural analysis of the polished samples was carried out using a MEIJI ML 7100 optical microscope. Moreover, SEM

**Fig. 1.** Dimensions of the tensile test sample.

images for micro-structural studies were obtained using a JEOL JSM 6060 model device. Grain size measurements of the extruded samples (vertical and parallel to the extrusion direction) were conducted using the MSQ Plus Image Analysis System according to ASTM E112.

In addition, micro-hardness measurements of the extruded samples were carried out using an HMV-2 SHIMADZU microhardness measuring device with a measurement precision of $\pm 0.01 \mu\text{m}$. The load applied during hardness measurements was 50 g and the period of the application was 10 s. The mean of five measurements was taken for each sample. The tensile test was applied to the Al–Si and Al–Mg alloys using a 20 kN-capacity ZWICK tensile testing device. The tensile test was conducted at a tensile speed of $3 \times 10^{-5} \text{ m/s}$. Samples for the tensile test were prepared in accordance with the ASTM E8M standard. Fig. 1 illustrates the dimensions of the tensile samples.

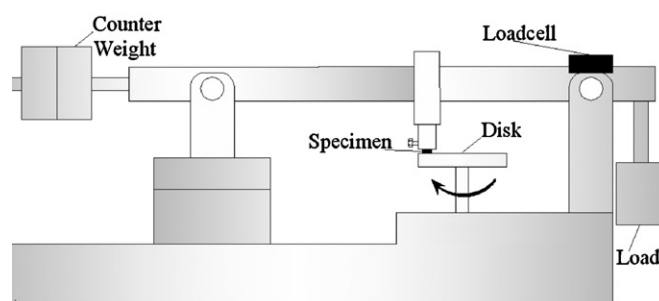
The extruded samples were subjected to wear test using a pin-on-disc type wear device (Fig. 2) at room temperature at a sliding speed of 1 m/s and under 10 N, 20 N and 30 N loads. Wear samples were prepared in cylindrical form with a 10 mm diameter and a 7 mm height. Wear tests were conducted at four different wear distances (300 m, 600 m, 900 m and 1200 m). Acetone was used to clean the wear samples and the disc before the tests. Wear results were assessed depending on the weight loss in the samples and weighed using scales with a 0.1 mg precision before and after the experiment.

The weight losses were assessed by measuring the samples after each 300 m. The counter-material used was AISI 4140 steel with a hardness of 60 HRC. The worn samples were examined using an SEM in order to determine the wear mechanisms of the worn surfaces.

3. Results and discussion

Fig. 3 illustrates the optical microscope images of die cast Al–Si and Al–Mg alloys used in this study. The images illustrate that the microstructures of both the alloys are dendritic. No pores are visible in the microstructure. While the primer α Al grains are surrounded by Al–Si eutectic in the Al–Si alloy, they are also surrounded by Al–Mg eutectics in the Al–Mg alloy.

Fig. 4A and C illustrates the optical microscope images of Al–Mg and Al–Si alloys that are parallel to the extrusion direction and extruded at the ratio of 2, while Fig. 4B and D illustrates the optical microscope images vertical to the extrusion direction. As is seen from the images (Fig. 4), the grains are elongated in the direction of extrusion. The images of the same alloys have been taken vertical to the direction of extrusion (Fig. 4B and D) show the appearance of an equiaxed grain structure. Such a result reveals that the grain

**Fig. 2.** Pin-on-disc wear test machine.

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