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The influence of microstructure on the shock and spall behaviour of the magnesium alloy, Elektron 675

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Abstract

Alloying elements such as aluminium, zinc and rare earth metals allow precipitation hardening of magnesium (Mg). The low densities of such strengthened Mg alloys have led to their adoption as aerospace materials and (more recently) they are being considered as armour materials. Consequently, understanding their response to high strain-rate loading is becoming increasingly important. Here, the plate-impact technique was employed to measure stress evolution in an armour-grade wrought Mg alloy (Elektron 675) under one-dimensional shock loading. The effects of sample orientation and heat treatment were examined. The spall behaviour was interrogated using a heterodyne velocimeter system, with an estimate made of the material's spall strength and Hugoniot elastic limit (HEL) for both aged and unaged materials. In particular, it is shown that the HEL and spall strength values are higher along the extrusion direction. It is thought that this is caused by striations of relatively small grains that run along the extrusion direction.

Keywords: Fracture mechanisms; Spall; Shock waves; Impact testing; Plate impact

1. Introduction

Elektron 675 is a new alloy produced by Magnesium Elektron Ltd., which is based on the magnesium–yttrium–gadolinium ternary system [1]. This alloy is relatively strong compared to other magnesium alloys (such as AZ31B), with strength values approaching that of armour-grade aluminium alloys. For armour applications, magnesium alloys have an advantage in that their density is relatively low compared to other armour materials and therefore the weight of the overall structure can be minimized for a given level of protection. Early studies on the ballistic performance of magnesium alloys date back to World War II [2]. However, previous studies have precluded the use of magnesium alloy armour on account of its propensity to spall during ballistic attack. Nevertheless, recently there has been resurgence in interest in using magnesium alloy for armour applications [3]. Furthermore, magnesium and its alloys are extensively applied in the aerospace and automotive industries where dynamic straining of structures is quite common or where explosive forming may be necessary for production purposes [4,5]. Consequently, understanding the response of these materials under dynamic stimuli is of interest.

As with most metals, magnesium and its alloys plastically deform principally by the glide of dislocations along preferred crystallographic planes in the close-packed lattice directions. Magnesium has a hexagonal close-packed (hcp) structure, with the easy glide of dislocations occurring along the basal, prismatic and pyramidal planes in the $\langle 11\bar{2}0\rangle$ directions, commonly referred to as $\langle \boldsymbol{a} \rangle$ type slip systems [6], as shown in Fig. 1a. However, it has been shown that to accommodate compatible plastic strains in

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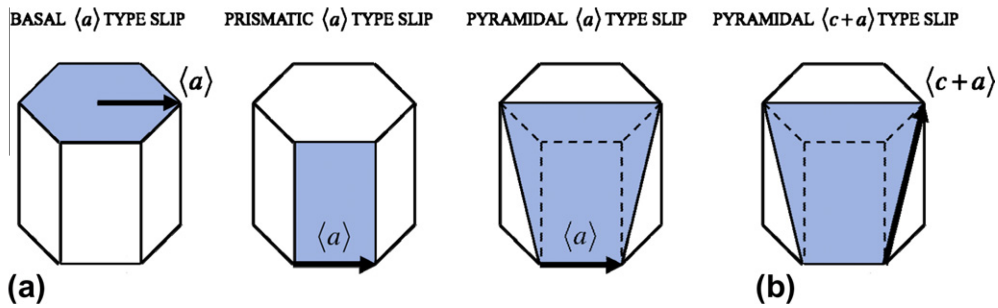

Fig. 1. (a) Basal, prismatic and pyramidal $\langle a \rangle$ type slip systems, (b) pyramidal $\langle c+a \rangle$ type slip system.

a polycrystalline metal, a total of five independent slip systems are required [7]. Due to the three easily activated $\langle \boldsymbol{a} \rangle$ type slip systems having the same slip direction, they reduce to only four independent slip systems [8]. Thus to meet the criteria for compatible plastic strains, a further non-$\langle \boldsymbol{a} \rangle$ type slip system must be activated. Typically this is accommodated by a so-called $\langle \boldsymbol{c}+\boldsymbol{a} \rangle$ type slip system, as shown in Fig. 1b. However, it has been argued that incompatible plastic strains in polycrystalline metals can also be accommodated by the activation of deformation twinning [9]. This results in a reorientation of the crystal lattice into a mirror orientation, thus accommodating plastic strain and more importantly, typically reorientating the crystal lattice for easy $\langle \boldsymbol{a} \rangle$ type slip. Numerous studies of magnesium alloys (and hcp metals in general) have shown that deformation twinning becomes more prevalent as strain rate is increased [10]. indicating that this is the preferred mechanism for accommodating plastic strains not compatible with $\langle \boldsymbol{a} \rangle$ type slip systems at high strain rates.

Compared to other metals, such as copper, aluminium and titanium, where there is a wealth of data on their shock behaviour, magnesium and its alloys have received relatively little attention. Nevertheless, several papers exist that describe the high strain-rate response of magnesium from either a theoretical and/or experimental point of view (e.g. see Refs. [11–14]).

Early work has been carried out by Schmidt et al. [15], who measured the spall strength of AZ31B-H24 and reported a value of ~1.5 GPa for the onset of incipient spall at room temperature. Fuller and Price [16] concentrated on the elastic–plastic response of the alloy ZW3 and showed that it exhibited a strong elastic–plastic response. They also observed a relaxation in stress behind the shock front prior to the arrival of the release wave that they attributed to slip on the basal plane.

Marsh has previously presented the Hugoniot for AZ31B [17], and shock traces for this material have also been reported by McQueen et al. where a spall strength of ~0.8 GPa (calculated from the free surface velocity of the pull-back signal) was seen [18]. The spall strength of Mg95 (99.95 wt.% Mg) has also been studied by Kanel and co-workers at various initial temperatures [19]. In this work they showed that the spall strength dropped off as the temperature approached the melting point of the metal. However, unexpectedly large values of the elastic precursor wave were observed at temperatures approaching the melting point. This was attributed to spontaneous nucleation of point defects at the elevated temperatures. Further, simulation work on the spall behaviour of Mg95 was carried out by Kanel et al., where an empirical constitutive relationship was established to describe the fracture rate as a function of the tensile stress, damage value and temperature [20]. Further spall data for magnesium and a magnesium–lithium alloy have been provided by Golubev et al. [21] which were shown to be comparable to the results from McQueen et al. [18].

More recently, Millett et al. have studied the alloy AZ61 under shock loading conditions, reporting a HEL of ~0.2 GPa for this alloy [22]. They also used longitudinal and lateral manganin stress gauges to evaluate the shear strength behind the shock front. Further, they identified tentative evidence of elastic precursor decay occurring in this alloy. Precursor decay has also been observed in other magnesium alloys such as magnesium MA2-1 [23].

In this work we examine the effect of the microstructure on the shock behaviour of the Elektron 675 alloy by comparing two different heat treatment conditions. We also report experiments where the alloy was loaded both along and perpendicular to the extrusion direction to examine what effect the anisotropic microstructure has on spall strength.

2. Experimental

2.1. Material

Elektron 675 was supplied by Magnesium Elektron Ltd. in two conditions: the cast then extruded "F condition" and the cast, extruded then artificially aged "T5 condition". Each condition was sectioned and samples for plate-impact testing cut from the longitudinal or transverse directions as required; each sample was subsequently machined flat and parallel to ±5 μm. A schematic illustrating where the samples were cut from is shown in Fig. 2. Subsequently, in the text we have referred to samples that have been shocked along the extrusion direction as "Face 3 samples" and samples that were shocked perpendicular to the extrusion direction as "Face 1 samples".