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The effect of internal stresses due to precipitates on twin growth in magnesium

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ABSTRACT

Twinning is an important deformation mode in hexagonal close packed (HCP) metals, including magnesium alloys. Precipitates are used to provide strengthening in many of these alloys. The effect of precipitates in strengthening against deformation by slip is well understood, but this is not the case for twinning. Recent studies have indicated that precipitates are usually not sheared by twins, but the Orowan law for strengthening against slip by dislocation bowing does not give a good prediction when applied to twinning. It has therefore been proposed that the dominant strengthening effect inhibiting thickening of a twin arises from an additional back-stress that results from embedding a unsheared precipitate in twinned matrix. The present paper uses an Eshelby model to assess the influence of precipitate shape and habit on the internal stresses that arise from embedding a non-shearing precipitate in a $\{10\bar{1}2\}$ twin (the dominant twin type). It is demonstrated that the elastic stresses generated easily exceed the critical resolved shear stress for activation of slip and therefore plastic relaxation is to be expected. In all cases, the predicted plastic zone is confined to a region local to the particle. The implications of these predictions for design of precipitation strengthened HCP alloys are discussed.

1. Introduction

Twinning is an important deformation mode in hexagonal close packed (HCP) metals, with the $\{10\bar{1}2\}$ twin mode being one of the easiest mechanisms to activate during room temperature loading [1]. In magnesium, the easy activation of this twinning mode combined with the strong textures generated in wrought products is responsible for mechanical asymmetry; an undesirable difference in compressive and tensile strength [2,3].

Given its importance, the $\{10\bar{1}2\}$ twin mode has been studied extensively in magnesium alloys and other HCP metals [1]. Many of these alloys contain second phase precipitates, either formed deliberately during an ageing treatment to provide strength, or as a result of impurities or process route. The important role such particles can have in increasing strength by inhibiting slip is well understood through relationships such as the Orowan equation and is fundamental to alloy design. However, despite the importance of twinning as a deformation mode in HCP metals, the role of precipitates on twin mediated deformation is poorly understood [1]. A number of studies have demonstrated that twin nucleation is not suppressed by the presence of precipitates. Indeed, it is commonly observed that the presence of precipitates leads to a greater number of smaller twins (when compared to the same material in a precipitate free state) [4–6]. However, non-shearing precipitates are seen to act as effective obstacles against twin growth, significantly increasing the stress required to thicken twins [2–5,7]. This effect might be exploited to increase strength and reduce anisotropy in HCP metals, overcoming two major limitations preventing their wider use. The promise of this approach has led to a number of studies focussed on understanding precipitate/twin interactions, focussing on age hardenable magnesium alloys [2,3,5,8–11]. However, there remains no model or law to predict how precipitates influence the stress required for twin growth.

An early study of precipitate/twin interactions in magnesium was performed by Ghaghouri et al. [4,12], who investigated the Mg–Al system (the basis of the most widely used commercial magnesium alloy, AZ91). They demonstrated that when twins are very small compared to the precipitate size, they can be blocked by precipitates. As the twins grow, they can attempt to avoid precipitates by local deviation of their habit (K_1) plane. This requires multiple twinning dislocations to be introduced into the plane, with an associated energy cost (discussed in detail by Ghaghouri et al. [4,12]). In addition, any bulging or local thickening of the twin

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boundary will be opposed by a back−stress induced by the surrounding matrix, and there is thus a strong energy penalty against the twin deviating from its ideal lenticular shape. By the time the twins have grown enough to produce measurable macroscopic yield, they were observed to have engulfed some of the precipitates and deviations in the habit plane were generally observed to be small (compared to the thickness of the twin).

Gharghouri et al. demonstrated that the precipitates, which form mainly as plates on the basal plane in Mg−Al alloys, are not themselves sheared when engulfed by a twin [4,12]. This has since been shown to also be the case for Mg−Zn alloys, where the precipitates form as rods parallel to the c−axis [5,6]. The strain incompatibility that necessarily arises from embedding an unsheared precipitate into sheared (twinned) matrix will generate a very large strain (and stress) in the matrix if accommodated elastically. No evidence for such large strains were observed, but instead Ghaghouri et al. identified a concentration of dislocations in the region where high stress would be expected, indicative of a plastic relaxation process [4]. Evidence of plastic relaxation around precipitates in magnesium alloys has since been identified in other alloy systems with other precipitate types [9,11].

Attempts have been made to predict the strengthening effect of precipitates against twin growth by applying the Orowan−Ashby equation to predict the stress required to bow the twinning dislocations around the precipitates [9]. Although this approach works well to calculate the strengthening against slip, it has been demonstrated that it greatly under−predicts (e.g. by a factor of 4) the strengthening effect of precipitates against twin growth [9]. Instead, it has been argued that it is the additional back-stress expected when shear resistant particles become embedded in the twin that provides the dominant contribution to strengthening against thickening of the twin [6,8,9].

Particles can also influence twin growth before the thickening stage. The initial stage of twin growth involves the twin tip propagating from the grain boundary region in which it nucleated to the opposite grain boundary. This is usually assumed to be very rapid. However, in the case where precipitates are present, it is possible that the twin tip will become blocked in this initial growth stage [7]. The blocked twin will then thicken, leading to an increase in the back-stress against further twin growth. A situation can eventually be reached where the twin thickening is stalled. To overcome this stalled growth, sufficient additional stress must be imposed to bow the thickened twin around the blocking precipitate [7]. Since multiple twinning dislocations have to be bowed simultaneously to unblock the growth of the twin tip, the required stress is much higher than for the bowing of a single dislocation during twin thickening [7].

Regardless of how the twin overcomes the particle, once an unsheared particle becomes fully embedded in a twin, it will necessarily lead to an additional back-stress as a result of the misfit between the sheared matrix and unsheared precipitate. This misfit stress is expected to be partially plastically relaxed (by dislocation slip), and this adds a considerable complication in determining the inhibition that precipitates will have against twin growth. The dislocation slip processes themselves (required to relax the back-stress) will be influenced by factors such as alloy solute content and neighbouring precipitates. Furthermore, the misfit strain consists of both <a> and <c> components, but the critical resolved shear stresses required to activate the required plastic relaxation processes in these directions are very different. These complex interactions are poorly understood but will be important in determining the stress required to grow twins in precipitate containing alloys.

The aim of the present work was to better understand the misfit stresses that will be generated and the likely extent of plastic relaxation that will occur around unsheared precipitates of different shapes and habits when embedded in a $\{10\bar{1}2\}$ twin. The calculations are performed for magnesium, but have implications for strengthening against twin growth in other HCP alloys. It should also be noted that the case considered here is a specific example of the more general problem of stress induced grain boundary migration [13,14] and the analysis could also be applied to the more general case of a grain boundary passing through a distribution of unshearable precipitates, providing the correct transformation strain tensor was applied.

The present results provide an important step in attempts to better understand, and eventually model, the strengthening effect of precipitates against twinning. This could ultimately lead to a new class of HCP alloys containing precipitates specifically optimized to strengthen against deformation twinning.

2. Theory

Deformation twinning is commonly observed in HCP metals due to the limited ability of slip to accommodate an arbitrary shape change. This study focusses on magnesium alloys, and in common with HCP titanium and zirconium, there is no easy slip mode that can accommodate strains along the c−axis direction. Loading along this direction therefore usually induces yield by twin nucleation and growth, once a critical stress is reached. The most common twin in HCP metals is the $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ mode, which in magnesium produces an extension along the c-axis direction. Once nucleated, these twins usually grow very rapidly, since the $\{10\bar{1}2\}$ twin boundary is highly mobile in HCP metals [1]. Indeed, unlike a random high angle grain boundary, the growth of this twin type is usually not limited by boundary mobility [1], but by the back−stresses generated as it thickens [15,16].

In a precipitate containing alloy, the twin must grow though a distribution of particles with a different crystal structure to that of the matrix if it is to thicken. The material in the twin is sheared with respect to the parent, and a precipitate entering into the twin has to

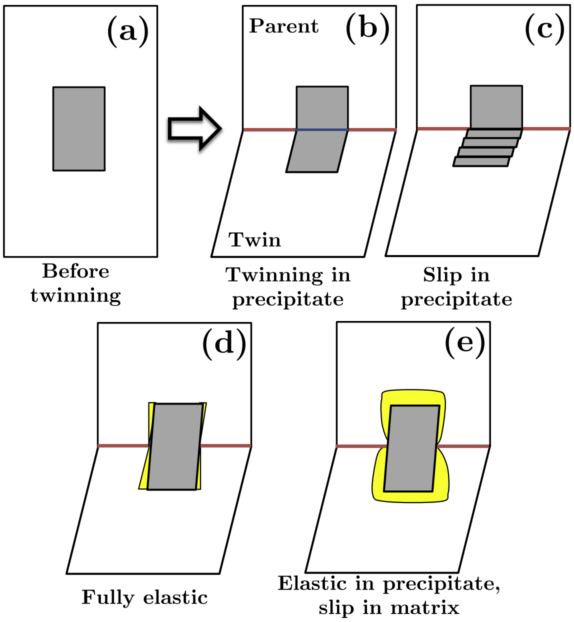

Fig. 1. Schematic showing the possible ways a non−shearing precipitate can accommodate the misfit strain when it becomes engulfed by a twin (a) before twinning, (b) twinning in the precipitate, (c) slip in the precipitate, (d) elastic deformation only (matrix and precipitate), (e) elastic deformation (precipitate) and elastic-plastic deformation (matrix).