Deformation Mechanisms in Mg Alloys and the Challenge of Extending Room-temperature Plasticity

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Magnesium alloys show promise for application in formed components where weight saving is an advantage. In most instances forming is carried out at elevated temperatures. However, there are considerable gains to be had if forming can be carried out under ambient conditions. The present article outlines some of the difficulties that lie in the way of achieving this objective. The underlying metallurgical characteristics of the issues are considered and means for overcoming them are discussed. It is concluded that a combination of microstructure and texture control remains a promising strategy.

INTRODUCTION

The difficulty of forming magnesium alloys under ambient conditions has been long known.[1] The challenge is best illustrated by their comparatively low values of uniform elongation, tensile reduction of area, sheet forming limits, cold rollability and bendability (e.g., Reference 2). This feature of the metal and its alloys is frequently ascribed to a shortage of independent deformation modes.[1,3,4] The deformation is dominated by basal slip, which gives no deformation along the c-axis of the Mg hexagonal close packed unit cell. However, such deformation can be accommodated by twinning and <c+a> slip.[4] For contraction along the c-axis these only activate once high stresses are attained. It is also true that twinning can directly give rise to void nucleation.[5] Thus, it is probably best to view the problem not so much as a lack of deformation modes but rather a consequence of the characteristics of the particular deformation modes that activate, particularly those that grant c-axis contraction.

This effect is accentuated by the tendency of magnesium and its alloys to develop sharp single fiber textures during wrought processing. The basal plane rapidly aligns itself parallel to the direction of predominant material flow. Thus, rolling produces fiber textures characterized by a basal plane near to the sheet plane. Extrusion gives a predominant c-axis alignment perpendicular to the extrusion direction.[6–8]

How would you…

…describe the overall significance of this paper?

This paper outlines key challenges facing the development of ductile wrought magnesium alloys. It shows that microstructure control remains a profitable avenue by which these challenges may be overcome. There are some important outstanding scientific questions pertaining to twinning, the answers to which will greatly benefit magnesium alloy development.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

One of the keys to ductile magnesium alloys is a microstructure free of void-initiating particles and with a grain size and texture that promotes uniform plastic deformation. Rare earth alloying addition and the suppression of deformation twinning are important tools to achieve this end. Predicting important twinning sequences is an objective for future work.

…describe this work to a layperson?

Magnesium is an attractive metal due to its low density. More widespread use of this material is being held back by its high cost in relation to competing metals such as aluminum. The present work examines how controlling the metallurgical structure can increase the ease with which the material can be fabricated. This, in turn, promises to lower part cost.

It comes as no surprise that efforts to improve the ambient formability of magnesium alloys have been directed towards lowering the stress for non-basal slip activity, by adding Li for example.[9] A related effect seems to accompany low levels of other solute additions.[10] Texture modification using equal channel angular extrusion (ECAE) has also been successfully employed to increase the ductility. Mukai et al.,[6] Agnew et al.,[7] and Kim and Jeong[11] have shown increases in uniform elongation from ~0.1 up to ~0.6 in ECAE material. An increase in uniform elongation is also seen when comparing samples cut perpendicular to the extrusion direction with those cut parallel to it, for conventionally processed material.[12] Sheet formability is known to improve with increasing departure from standard basal textures.[13]

One rationale for these effects is that texture optimization serves to delay failure by permitting deformation to occur at stresses under those at which void nucleation occurs. This effect arises because basal fiber textures generally represent the "hardest" textures (for material tested along the direction of primary material flow). Any texture with less of a conventional basal fiber will deform under lower stresses. This of course will only last until the basal texture reforms. As it does, the material hardens due to texture change. This also provides a ductilizing effect, which serves to push the Considère strain out to higher values. Thus, the benefit to be had in this regard is sensitive to the rate of texture evolution.

A lower limit for the rate of texture evolution in the absence of twinning may be obtained from the behavior observed in hot deformation. Here, twinning is suppressed by the elevated temperatures. In such cases, basal textures can take strains of 0.5–0.6 to form.[14] These values correspond quite well to the high uniform strains reported by Kim and Jeong for their ECAE material, which displayed strong off-basal textures.[11]

However, non-conventional deformation processes such as ECAE are unlikely to find widespread application. It is thus more desirable to find means of modifying the texture though alloying control. Additions of rare earth elements have shown promise in this regard (e.g., Reference 15). Grain refinement has also long been known to raise the ductility of magnesium and its alloys.[16] The present short paper provides an overview of work, largely carried out by the group at Deakin University, that examines how grain refinement, texture control, and deformation mode manipulation might be achieved for improved ambient ductility in conventionally processed material. First, though, ductility is examined in a little more detail.

DUCTILE FAILURE

It is worth considering briefly the nature of ductile failure in magnesium alloys and how the failure mechanisms might be linked to the issues raised above. Observations of damage near to tensile fracture surfaces in the common wrought alloys Mg-3Al-1Zn (AZ31), Mg-1Mn with <0.5wt.% of rare earth element addition (ME10), and Mg-6Zn-0.5Zr (ZK60) reveal two distinctly different sources of damage (Figure 1): twins and intermetallic particles. Clearly, designing alloys that contain limited fractions of these features will be expected to improve the ductility.

Despite a possible role of intermetallic particles in failure, pure magnesium does not generally display the same dramatic improvement in ductility that is encountered when aluminum is purified, for example. This is consistent with the rather unique characteristics of the deformation described above, one of which has to do with deformation twinning. However, the effect of twinning can be minimized by refining the grain size.[17,18] Combining this with alloy purification has been shown by Wilson and Chapman[17] to lead to considerable improvements in tensile reduction in area in conventionally extruded samples.

In that work, reduction in area values as high as 55% were obtained at room temperature for material with a mean grain size of ~1.5 μm. This compares to values of 10–15% obtained for grain sizes of 10–20 μm, a result that is in good agreement with other workers (e.g., Reference 18). Mimicking such an improvement in a commercial alloy subjected to conventional processing is clearly an attractive proposition. The challenge is thus to combine texture optimization with highly grain-refined structures free of brittle particles. For extrusion alloys it is also highly desirable to keep alloy addition to an absolute minimum. This ensures maximal extrusion rates. The same restriction does not hold for rolled alloys.

GRAIN REFINEMENT

One approach to refining the grain structure of material produced using conventional extrusion is to delay the grain coarsening that rapidly follows the exit of material from the extrusion die. To estimate the roles of alloying addition on this growth, a series of hot deformation and holding experiments were carried out. Alloys employed were both experimental (Mg-aX-bY,

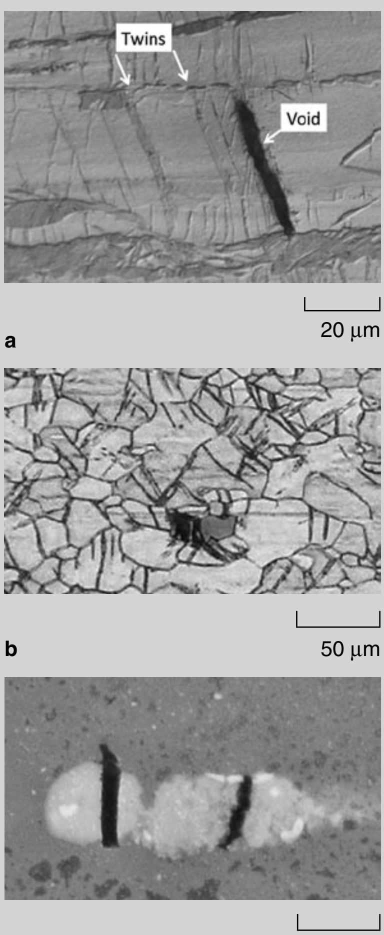

Figure 1. Formation of damage in magnesium alloys strained to failure in tension parallel to the extrusion direction (horizontal). (a) Alloy ZK60 tested at room temperature showing damage at twins, (b) alloy AZ31 tested at 100°C, and (c) alloy ME10 tested at room temperature, showing void formation at fractured particles.

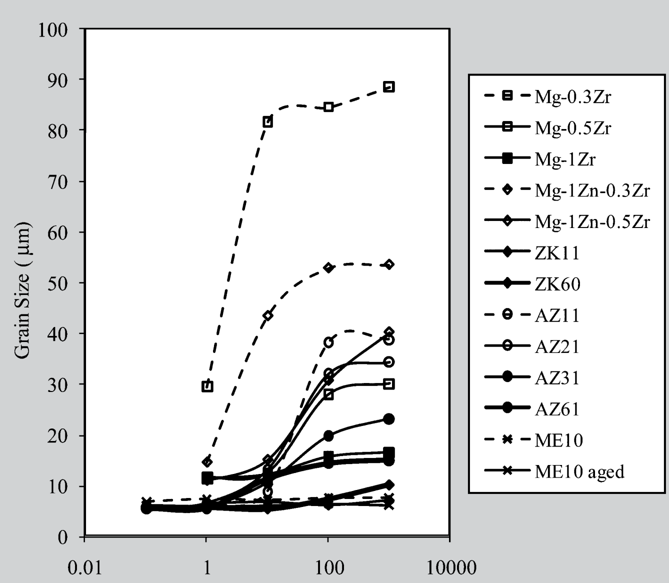

Figure 2. Evolution of grain size in different alloys, during holding at temperature, following hot deformation in compression to a strain of 1.5 at 350°C and a strain rate of 0.01 s^{-1}. The structure was dynamically recrystallized at the end of the deformation.

where a and b are the weight percentages of elements X and Y) and conventional (XYab, where a and b refer to the rounded weight percentages of element abbreviations X and Y – A=Al, Z=Zn, M=Mn, K=Zr, E=rare earth elements, usually in the form of a Ce-rich "misch-metal"). The material was deformed in compression to a strain of 1.5 to permit a dynamically recrystallized structure to form. The evolution of grain size was then monitored with holding time at temperature following deformation. The results obtained are given in Figure 2.

The conditions employed in these tests (350°C and a strain rate of 0.01 s^{-1}) lead to flow stresses not too far removed from those expected in commercial extrusion so the rapid rate of coarsening seen in some of the alloys can be expected to have an impact on production. It is clear that the leaner compositions tend to favor grain coarsening and that in the richer commercial grades, AZ61 and ZK60, coarsening is suppressed. High levels (~1%) of zirconium are also effective in reducing grain growth but it is usually difficult to retain much more than ~0.7% through solidification. Of considerable interest are the retention of fine grain sizes in the Mn- and rare-earth-containing alloy. It is apparent that small (<0.5 wt.%) "micro-alloying" additions of rare earth elements to Mn-containing alloys may provide opportunity for grain refinement in commercial grades. These findings are of no great surprise (e.g., Reference 1). But the key to new alloy development is in finding the optimal rare earth elements to add and also in further quantifying the coarsening to enable optimal process control.

It should also be mentioned that considerable success has been had by many authors in refining the grain size using non-conventional processing routes such as ECAE[19] and high-pressure torsion.[20] It is worth pointing out, however, that high reduction hot rolling can also be employed to produce refined grain structures.[21,22] If edge cracking can be avoided, considerable gains in strength/ductility balance can be attained. For instance, alloy AZ31. with a grain size of 2.2 μm, has been produced using heavy single-pass rolling. A yield strength of 260 MPa with a uniform elongation of 0.22 was obtained.[22]

TEXTURE CONTROL

A number of authors have pointed to the favorable effects that some rare-earth alloying addition can have on texture sharpness.[22–25] With appropriate levels of addition, weaker textures result. In extrusion, it has been found that a particular component is favored in rare-earth alloys: $<11\bar{2}1>$ parallel to the extrusion direction.[24,25] It appears that the nucleation of recrystallization at shear bands plays a role in the change in texture that accompanies rare earth element addition.[24–27] It is speculated that the retardation of recrystallization noted above may well also serve to promote shear banding

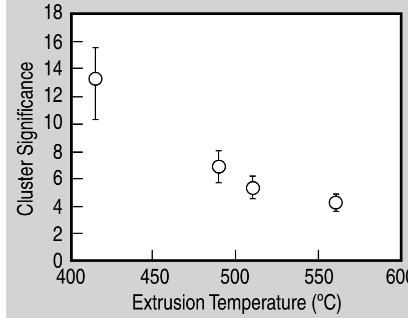

Figure 4. The change in clustering tendency of Gd at temperatures corresponding to the texture transition seen in Figure 3.

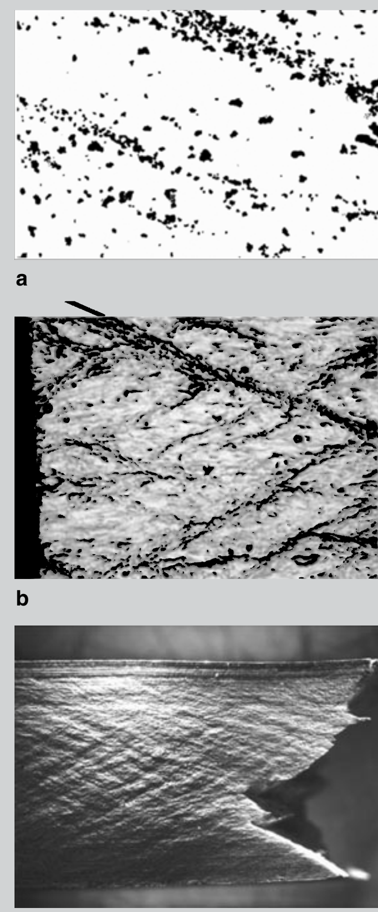
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Figure 5. (a) An EBSD map showing grains favorably oriented for basal slip under a vertical uniaxial load. (b) Surface relief showing concentration of strain in bands after compression testing. The mark corresponds to a grouping of favorably oriented "soft" grains. (Image height ~1 mm.). (c) "Edge on" view of the fracture surface of the same AZ31 plate used for (a) and (b) after tensile testing (tensile direction horizontal, also horizontal machining lines visible below top surface of sample). Diagonal bands of strain concentration can be seen and the fracture surface shows features consistent with strain localization on planes with a similar trace to the surface markings.

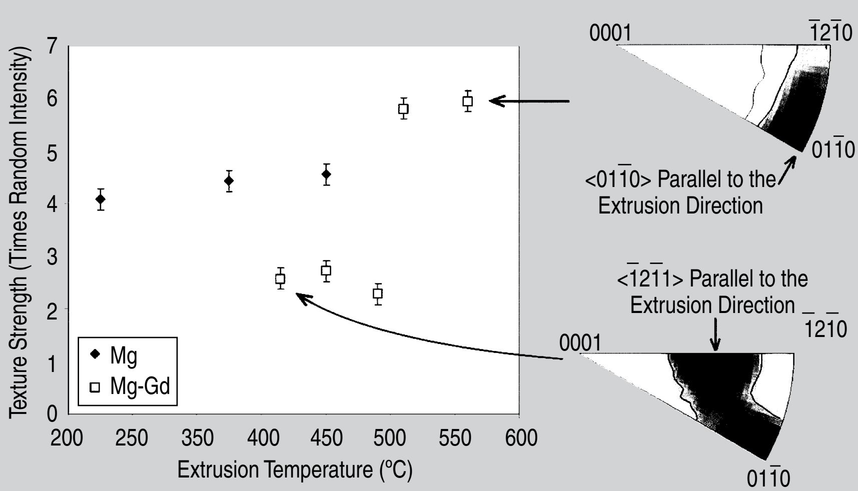


Figure 3. The influence of extrusion temperature on the texture of an Mg-Gd alloy and pure Mg.

because of a delay in dynamic recrystallization during working. Another possibility is that rare earth addition alters the strain rate sensitivity during deformation. Some suggestion for this can be found in work carried out on commercial alloy WE54.[28] Under appropriate conditions, dynamic strain aging type effects occur and the strain rate sensitivity drops below zero. Under such cases, shear banding is expected to become more prevalent (and possibly shear induced failure)[29] but more work is needed to understand the importance of these effects in magnesium alloys.

The favorable effect of rare earth elements on the texture seems to hold at least for the addition of La, Ce, and Gd.[24,25] In the case of a binary alloy based on the last of these, a transition in texture is observed with increasing extrusion temperatures. This is illustrated in Figure 3, where it can be seen that the "rare earth texture" gives way to a more conventional texture for extrusion temperatures greater than 500°C. The result is quite consistent with the idea advanced above in which the texture is modified in consequence of the retardation of dynamic recrystallization by rare earth addition. With rising temperatures this effect is expected to diminish.

Atom probe tomography of the extruded binary alloys employed in the texture study reported above shows that Gd atoms tend to cluster (Figure 4). This tendency drops rapidly with temperature over the range of temperatures that correspond to the transition in texture shown in Figure 3. More work is also required here to tie these effects together but it is apparent that optimal processing conditions exist for the best textures and that these may relate to the need to retain a certain level of solute clustering.

HOMOGENEITY OF TEXTURE

In attempting to combine grain refinement with texture control it is important to ensure that the orientations present are evenly distributed. If they are not, significant variation in strains over the microstructure can arise. This can lead to surface markings during forming and even a hastening of failure. An example of such strain partitioning is shown in Figure 5 where electron backscattering diffraction (EBSD) was employed to identify favorably oriented "soft" grains on the surface of an annealed commercial Mg-3Al-1Zn (AZ31) plate prior to compression testing. An image of the same region following compression to a strain of 5% is also shown. It is clear that groupings of grains favorably oriented for basal slip lead to strain heterogeneities. In tensile tests performed on the same material, failure follows these lines of strain concentration (Figure 5c).

TWINNING

Finally, it is acknowledged that grain refinement to the levels at which twinning is entirely suppressed are difficult to achieve. Thus we have made some attempt to characterize the effects on ductility of twins that form under c-axis extension (i.e., {10$\bar{1}$2} twins) and those that form under c-axis contraction (i.e., {10$\bar{1}$1} twins). It is seen that the former can serve to extend the uniform elongation if they activate during

Figure 7. (a)–(c) Twins seen during loading and unloading of cast AZ31 using in-situ tension. (a) Zero load, (b) loading, and (c) unloading. (EBSD band contrast images with twins in bold.) Inverse pole plots of the tensile direction showing (d) all examined grains and (e) grains that showed twinning on unloading.

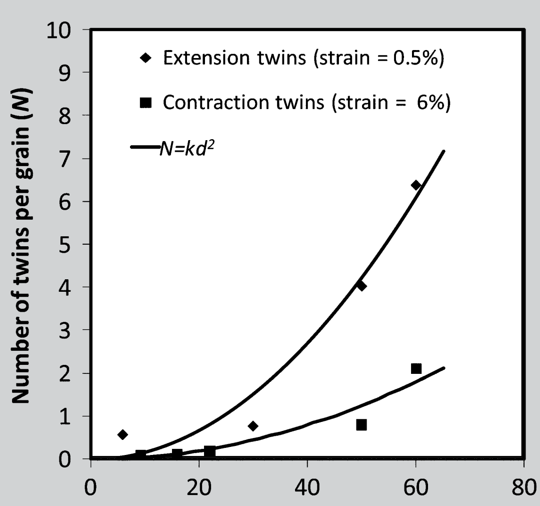


Figure 6. The influence of grain size on the number of twins seen per grain. (◆) Extension twins seen in compression of extruded bar along the extrusion direction for a strain of 0.5%, (■) contraction twins seen at a strain of 6% for tension along the extrusion direction.

tensile deformation[12] but that the latter tend to decrease both the uniform elongation and reduction in area.[5]

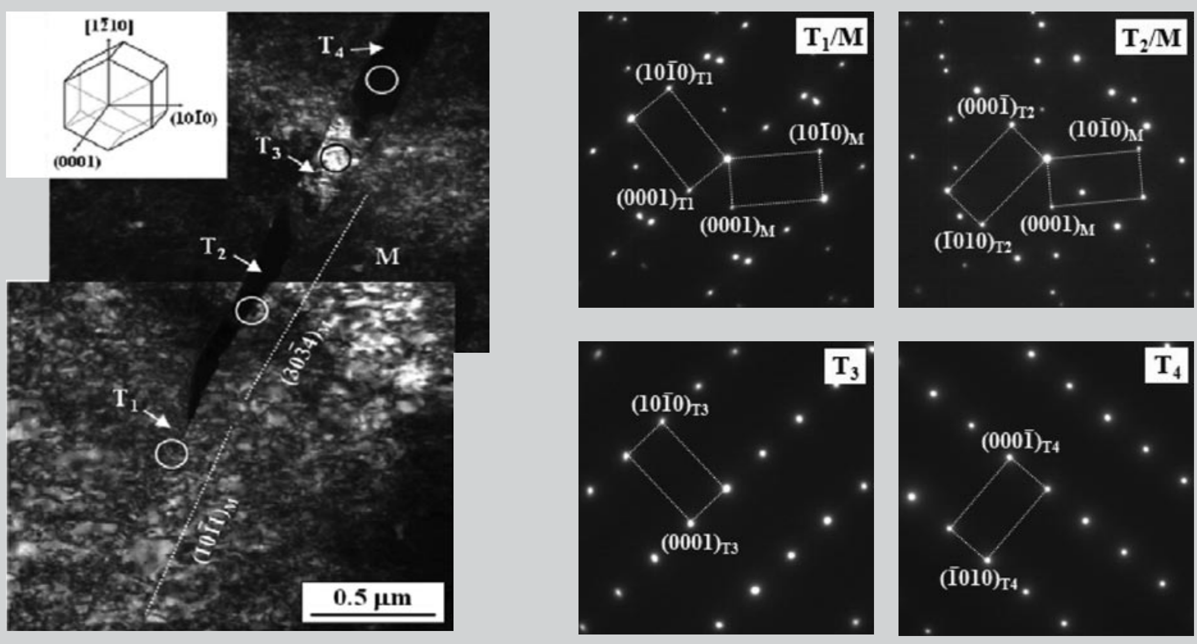
The frequency of twins in a commercial extruded alloy (AZ31) was measured as a number density per grain for tests carried out both in tension and compression. In both cases, twinning frequency per grain was seen to drop off with grain refinement (Figure 6). This can be readily rationalized if twinning nucleation occurs at a particular rate per grain boundary area.[30] It is also clear in Figure 6 that extension twinning occurs at lower strains than does contraction twinning. The latter obviously must require higher stresses and/or favorable dislocation structures for nucleation to occur.

It has also been found that both of these twinning modes display complex behaviors that are not yet fully understood. We have observed $\{10\bar{1}2\}$ extension twins to appear on a pre-polished free surface during unloading of coarse grained cast AZ31 material (Figure 7). This occurs mainly in grains oriented for tension in the basal plane. It appears that it results from the complex distribution of forward and back-stresses that arise in magnesium due to the variation of critical stresses for the different deformation modes.

In the case of $\{10\bar{1}1\}$ twins, it is well known that $\{10\bar{1}2\}$ twinning can readily occur in the twinned volume. The exact variants that form are not able to be predicted using simple models[31] and it thus appears that the complexity of the local stress distributions is also responsible for this. Furthermore, under the high stresses that arise near a fracture surface, it seems that multiple twinning can occur inside these twins to establish structures comprised of many subsequent twin events. An example is presented in Figure 8.

CONCLUSIONS

Future conventionally processed wrought magnesium alloys that display ductilities well in excess of those in current use are expected from combinations of micro-alloying addition of rare-earth elements with processing optimized for grain refinement and texture control. To create these new alloys and to generate accurate models for the ductility, it will be necessary to understand the nature of twin formation in magnesium alloys and the role of local stresses.



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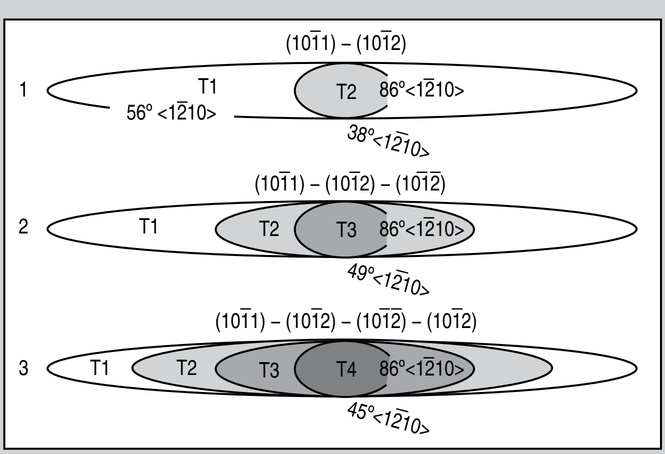

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Figure 8. (a) A TEM dark-field micrograph of a complex twin formed within the matrix grain M and composed of four segments T_1–T_4. The $(10\bar{1}1)_{T1,M}$ reflection was used to obtain the micrograph. The dotted lines indicate the approximate twin boundary traces in the matrix coordinates. The insert shows the orientation of the hexagonal lattice used in the analysis. (b) Selected area diffraction patterns obtained from the T_1,T_2,T_3, and T_4 twin segments, showing the rotation angles of approximately 56°, 39°, 50°, and 45°, respectively, relative to the matrix M around the common $[1\bar{2}10]_{T,M}$ axis. The corresponding zone axes are parallel to the $[1\bar{2}10]_{T,M}$ vectors. (c) Schematic representation of the suggested sequence of multiple $\{10\bar{1}2\}$ twinning events 1–3 occurring within the original $(10\bar{1}1)$ contraction twin and leading to the formation of the observed segmented twin.

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