

## Article

# The Effect of the Forming Mode on Twinning and Springback in the Bending-Dominated Forming of Magnesium AZ31 Sheet

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**Abstract:** The sheet metal forming of magnesium is challenging due to the material's complex springback behaviour, which is due to the tension/compression yield mismatch. In this study, three different AZ31 grain sizes are produced by a special heat treatment, while maintaining the material strength in uniaxial tension at a similar level. Pure, V-die and channel bending tests are combined with roll forming to compare bending scenarios with and without tension applied transverse and parallel to the bending axis. This is complemented with electron backscatter diffraction to measure the twinning type and twinning area fraction (TAF) in the tension and compression bending zones. Our study shows that, like conventional steel, when bending magnesium, springback reduces with the increasing level of the outer fibre bending strain, i.e., when the bend radius is decreased and the TAF increased. It is further shown that when tension is applied, the TAF increases. However, while in some forming cases, the increase in TAF leads to a clear reduction in springback, in other forming cases the effect of the TAF on springback is less pronounced. Overall, this study provides clear evidence that the twinning behaviour in bending magnesium is influenced by the bend deformation mode and that this influences the springback behaviour.

**Keywords:** magnesium; grain size; bending; springback; twinning area fraction



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## 1. Introduction

In bending and roll forming, magnesium sheet material deformation involves mechanical twinning formation. The microstructure behaviour is therefore important when estimating material behaviour [1].

Magnesium alloys generally show low formability at room temperature compared to ductile metals such as aluminium, steel and titanium [2]. In magnesium, deformation along the C-axis cannot occur via basal slip, which is why mechanical twinning must play a major role when deforming magnesium sheet [3]. Magnesium shows a high level of mechanical anisotropy, which changes the deformation mechanism throughout the thickness in bending [4]. Wu et al. [5] showed with in situ pinhole neutron diffraction that the material anisotropy due to twinning causes a neutral layer shift in bending. Fei-Fan Li et al. [6] and Tang et al. [7] successfully applied a Yoon 2014 yield function and crystal plasticity-based approach, respectively, to reproduce the neutral layer shift with numerical models. While Li et al. [6] observed strong correlation between the tensile and bend fracture limits of extruded AZ80 sheet, Desinghe et al. [8] showed for AZ31 that there is a clear difference between the yield strength in bending and tension and related this to the tension/compression yield mismatch.

One of the major defects that needs to be overcome when forming sheet metal is springback. Up to now, only a limited number of studies have focused on springback in bending magnesium sheet. Bruni et al. [9] showed that springback reduces with increasing forming temperature and a decreasing punch radius. Wang et al. [10] related the reduction

in springback to a reduced shift in the neutral layer position, while Kim et al. [11] suggested that the reduction in springback with increasing temperature is a result of an increase in the grain size (i.e., grain growth). Desinghege et al. [8] showed that the springback of an AZ31 alloy decreased with increasing grain size and the level of the outer fibre strain applied. In their study, the level of springback did not change with the C-axis orientation. Their study further suggested that the reduction in springback with increasing grain size may be related to an increase in mechanical twinning formation, i.e., an increase in the twinning area fraction (TAF).

Conventional sheet metal forming processes applied to automotive production generally involve a combination of bending and applied tension perpendicular to the bending axis to overcome springback [12]. On the other hand, roll forming, where a flat sheet is shaped to a complex cross-section by passing it through a set of profiled rolls, is increasingly applied to produce long automotive components from low-ductility metals such as magnesium and titanium [13]. Even though simple in tool concept, material deformation in roll forming is complex and includes bending combined with tension oriented parallel to the bend axis [14]. To successfully manufacture magnesium alloys in bending-dominated sheet forming operations, the effect of bending and tension on the twin area fraction that develops in the bending deformation zone and how this relates to springback and other shape defects must be explored, to enable the development of appropriate solutions for process design and part shape quality optimisation.

This study aims to analyse the relationship between the mechanical twinning behaviour and springback of magnesium sheet in bending deformation combined with tension. For this, the influence of forming and material parameters on springback is experimentally studied for different bend test and roll forming conditions. This is complemented with electron backscatter diffraction (EBSD) to determine the effect of the bending mode on the TAF. This work extends from the previous study in [9], which was limited to simple, pure and V-die bending deformation and did not analyse the twinning behaviour.

## 2. Materials and Methods

The key abbreviations and their definitions are given in Table 1.

**Table 1.** Key abbreviations and their definitions.

| Abbreviations: | Definition:                    |
|----------------|--------------------------------|
| SRB            | Springback Ratio               |
| RFS1, RFS2     | Roll Forming Sequences 1 and 2 |
| $\epsilon$     | True Outer Fibre Strain        |
| TAF            | Twinning Area Fraction         |
| PR             | Punch Radius                   |
| DR             | Die Radius                     |
| SW             | Side Wall                      |
| PB             | Pure Bend                      |
| VB             | V-Bend                         |
| CB             | Channel Bend                   |
| RF             | Roll Forming                   |

### 2.1. Material

Two Mg-3Al-1Zn alloys were analysed, with the first being a 1 mm thick cold rolled AZ31A sheet. The other material was a hot rolled block of 150 mm thickness, 300 mm length and 250 mm width that will be specified as AZ31B. Both materials showed very similar chemical compositions, and details can be found in [8]. A milling machine and a guillotine were used to cut the bend and roll forming samples from the AZ31A. This was followed by a heat treatment in a muffle furnace at 420 °C for 2 h and at 500 °C for 4 h, followed by air cooling, to produce grain sizes of 7 and 15 µm, respectively. The AZ31B magnesium block had an average grain size of 34 µm and was cut into plates of 1 mm

thickness by EDM cutting. For this, initially one sheet specimen was EDM cut from the block, followed by microstructure analysis to determine the C-axis orientation. Based on this, the subsequent samples were cut with the C-axis aligned with the sheet thickness. The EDM cutting process produced a shiny surface with no visible surface roughness marks or lines. In this way, in both materials, the C-axis was aligned with the sample thickness direction. Given that all test materials had a basal texture, the differences in mechanical behaviour anisotropy between them were assumed to be low.

## 2.2. Bending Deformation Analysis

Pure, V-die and channel bending and roll forming were analysed. Material deformation in pure bending is small but there are no friction effects. In the die V-bend test, material deformation can also be expected to be close to that of pure bending but with higher forming strains. In the channel bend test, a back tension is applied with a blank holder to introduce a tensile stress that is directed perpendicular to the bend axis. In roll forming, material is bent and restraughtened over the forming roll, which introduces tension parallel to the bend axis. The V-shape produced in roll forming and bending was kept the same in this study to directly compare the mechanical twinning formation between pure bending and bending with applied tension parallel to the bend axis in roll forming. Even though the overall shape was different between the channel-bent and the roll-formed profile shape, the level of deformation was kept similar as one of the conditions. This allowed one to compare the extent of twinning formation between pure bending and bending with tension applied perpendicular and parallel to the bend axis. All tensile and bend tests were performed on samples that were oriented transverse to the rolling direction, to conform with the roll forming process where the bending deformation is in transverse direction. The strain rate in all tests was between  $0.001 \text{ s}^{-1}$  and  $0.003 \text{ s}^{-1}$  while in the roll forming process it has been shown to be higher at approximately  $0.015 \text{ s}^{-1}$  [15]. Previous work suggests that at room temperature and within the small range of strain rate variation, the effect of the strain rate on the mechanical response and twinning can be considered low [16].

### 2.2.1. The Pure Bend Test

The pure bend test was performed with a stand-alone bend test device which is explained elsewhere [17]. The test includes two bending arms that are attached to the upper and lower crosshead and that can rotate to generate a pure bending moment onto the sample. The load is measured with a 5 kN load cell, while the bend curvature is recorded with a curvature gauge that is attached to the sample with rubber bands. The result is a moment curvature diagram. The sample curvature at the maximum bending moment at the end of forming,  $\frac{1}{R_b}$ , and after the bending moment is released to zero,  $\frac{1}{R_a}$ , are measured and used in Equation (1) to determine the springback angle  $\Delta\theta$

$$\text{Springback angle } \Delta\theta = \frac{180L}{\pi} \left( \frac{1}{R_b} - \frac{1}{R_a} \right) \quad (1)$$

Samples with 150 mm length and 25 mm width were tested with a crosshead speed of 1 mm/min and a gauge of 40 mm. The two maximum crosshead displacements of 60 and 100 mm gave final bend radii of 75 and 45 mm, respectively.

### 2.2.2. The V-Bending Test

The V-bend tests were performed with an upper punch and a lower die installed in an Instron 30 kN tensile tester. Two different punch radii of 10 and 15 mm were used, and the punch speed was 1 mm/min. The included bending angles at maximum load,  $\theta_b$ , and after release,  $\theta_a$ , were measured with an optical approach that involved taking photographic images that were imported into Solidworks. Further detail on the procedure is provided in [13], while Figure 1 illustrates the approach.

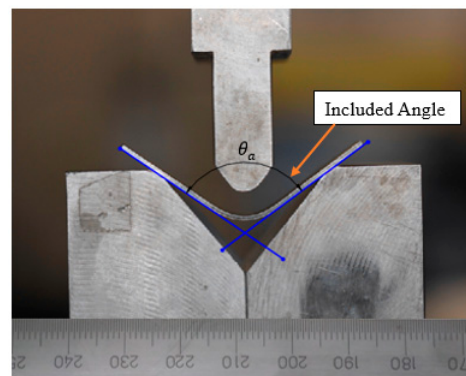


**Figure 1.** V profile image used in CAD to measure the bending angle after release.

### 2.2.3. The Channel Bending Test

The channel bending test was performed in an Erichsen Universal Sheet Metal testing facility, following the procedure used in [18]; the tool is shown in Figure 1. The square punch had a width,  $D_p$ , of 55 mm and a profile radius,  $r_p$ , of 6 mm, while the square die had a profile radius,  $r_d$ , of 4 mm. Normally, the clearance between the punch and die,  $C_1$ , should be 10% of the sheet thickness [19], but in this study it was 2.5 mm due to tool limitations.

The rectangular samples, which had a length and width of 170 mm and 35 mm, respectively, were positioned on the bottom blank holder surface. This was followed by the blank holder force being applied. The force was kept constant while the punch moved up at a speed of 10 mm/min to form the blank to a 40 mm channel depth. Two different blank holder forces (BHF) of 3 kN and 6 kN were investigated to achieve two different levels of tension applied perpendicular to the bend axis.

To measure the springback and the curl radius, samples were removed from the tool after forming, placed on a table and photographs taken. The springback angles were then analysed by applying the CAD software package “SolidWorks 2014” using a similar procedure as used in the V-bend tests and shown in Figure 1, i.e., the included angles were determined. For this, points O, A, B, X, Y and Z were marked (Figure 2), and point A was chosen as the intersection of the channel profile with a line 10 mm away and parallel to the bottom of the profile (OX), while Point B was positioned 20 mm away from point A on the profile. The punch corner angle,  $\theta_p$ , was measured between OX and AB. The die corner,  $\theta_d$  angle was determined between AB and YZ, while the curl was defined as the radius,  $r$ , between A and B [20].

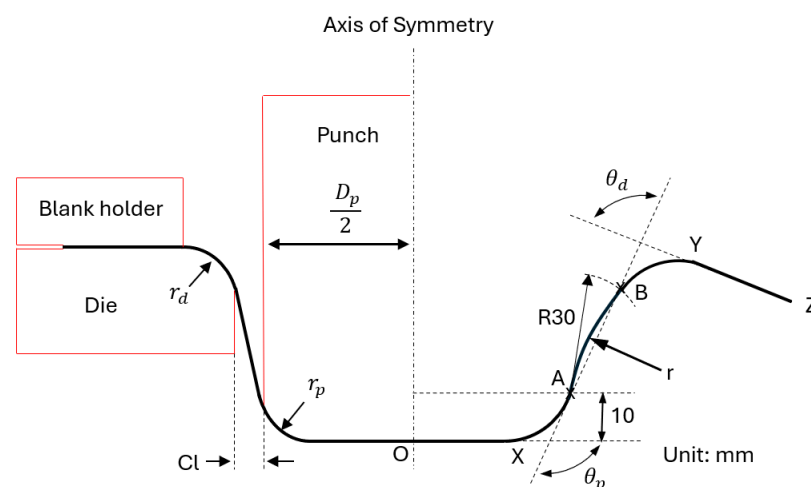


**Figure 2.** Channel bend test tool and channel cross-section after release from the tooling, showing method for springback and curl measurement.

The springback angles of the punch and the die side were determined with Equations (2) and (3), respectively.

Punch springback angle,  $\Delta\theta_p = \theta_p - 90^\circ$ , (2)

Die springback angle,  $\Delta\theta_d = \theta_d - 90^\circ$ . (3)

#### 2.2.4. Roll Forming

The sheet was formed to a V-profile shape like that produced in V-die bending using an industrial roll former (see Figure 3a). A typical roll stand design is shown in Figure 3b. Note that the constant arc length method was applied to develop the flower design [14]. In this method, the profile radius reduces in accordance with the increasing flange angle and can be calculated based on geometry. All the bottom shafts were fixed, and the top shafts adjusted vertically to set the roll gap to the material thickness of 1 mm. A constant line speed of 7.7 mm/s was used throughout the five forming stations without lubrication, to form a strip of 1000 mm length and 50 mm width. To apply different levels of tensile stress and strain in the strip edge, two bending progressions with different forming angle increment patterns were tested. Forming sequence 1 (FS1) applies a bend angle increment of  $10^\circ$  that is evenly distributed over the five roll forming stations, i.e.,  $10^\circ$ - $10^\circ$ - $10^\circ$ - $10^\circ$ - $10^\circ$  (see Figure 3c).

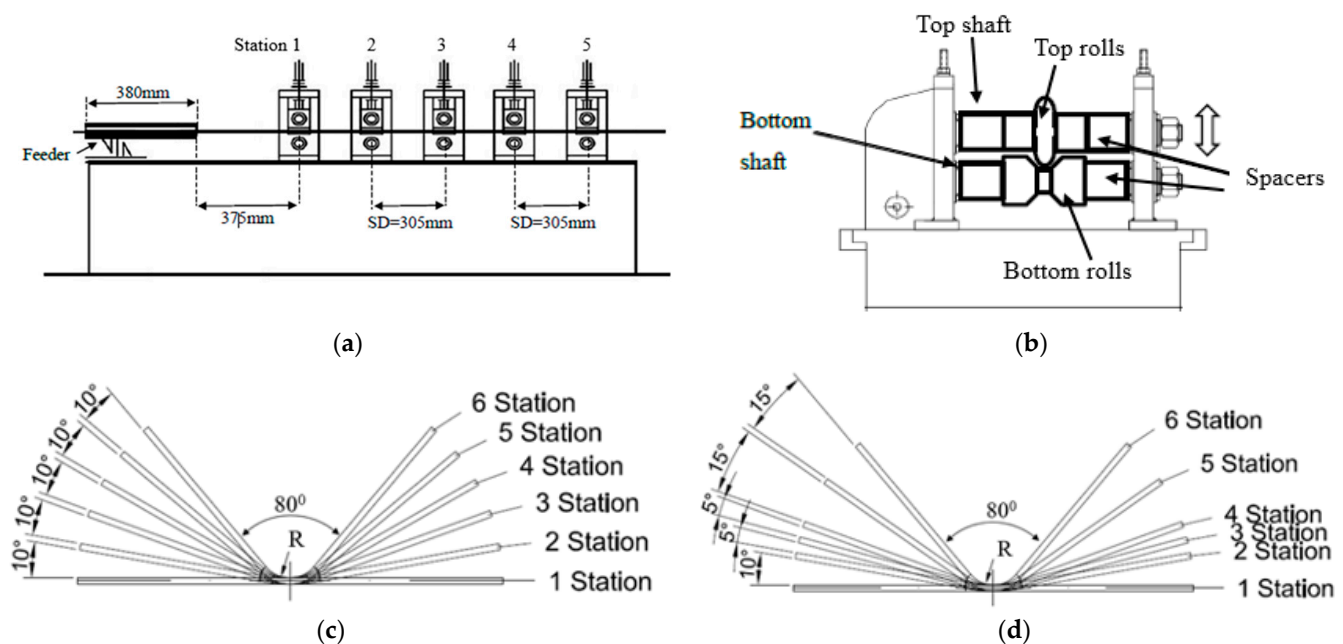


**Figure 3.** (a) Schematic representation of the roll forming facility. (b) Schematic representation of a roll stand. (c) Flower pattern for forming sequence 1 (FS1). (d) Flower pattern for forming sequence 2 (FS2).

Forming sequence 2 (FS2) has an uneven bend angle increment, 10°-5°-5°-15°-15° (Figure 3d) and therefore applies a different level of longitudinal tensile stress and strain in the flange edge [21]. Two different final forming radii of 5 mm and 15 mm were tested. While the smaller roll-formed profile radius of 5 mm conforms well to the bend radii of 4 and 6 mm that were produced in the channel bend test, the larger profile radius of 15 mm is the same as that formed in one of the V-bend test conditions.

The springback angle was determined with Equation (4).

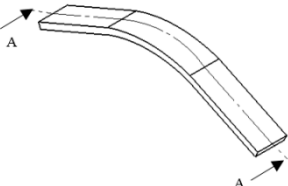
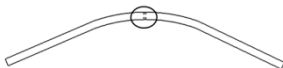
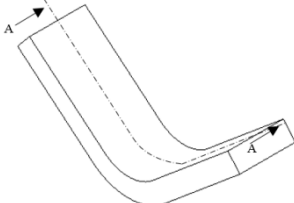
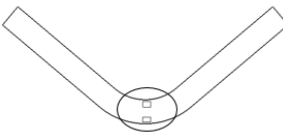
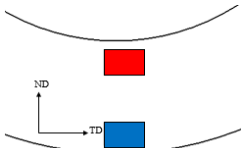
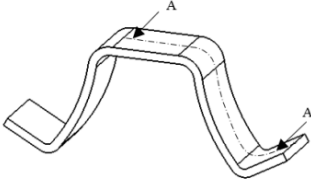
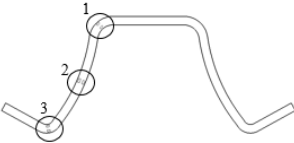
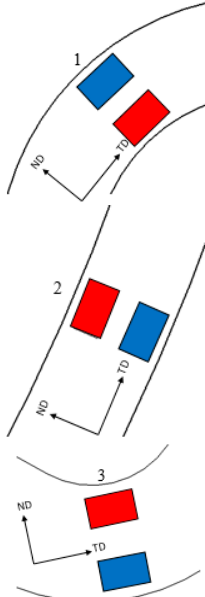
$$\text{Springback angle, } \Delta\theta = \theta_a - \theta_b \quad (4)$$

with  $\theta_a$  representing the inner profile angle of the roll-formed section after release from the roll former and  $\theta_b$ , being the final section angle formed in the final forming station. Equation (3) assumes that the final bending angle under load corresponds to the profile of the bottom roll in the last forming station.

2.2.5. The Critical Forming Zones

Using a diamond-cutting wheel, samples were cut after forming through the centreline (A-A cross-section view in dashed line) in the maximum curvature location of all deformed zones, as shown in Table 2. The critical zones are highlighted by circles. This allowed the analysis of mechanical twinning in both the tension and compression regions (Table 2). In the wall region of the channel-drawn samples, the material is bent and un-bent, which should eliminate any tension and compression zones. Despite of this, the wall channel zones were named as tension and compression to simplify the comparison of the results.

**Table 2.** The critical forming regions (compression highlighted in red and tension in blue) identified for EBSD mapping. ND and TD represent normal direction and transverse direction, respectively.

| Forming Mode           | 3D View                                                                             | Section A-A                                                                                                                                                   | Mapping Region                                                                        |
|------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Pure bend              |   |                                                                             |    |
| V bend<br>Roll Forming |  |                                                                           |  |
| Channel bend           |  |  <div><p>1. Punch corner</p><p>2. Side wall</p><p>3. Die corner</p></div> |  |

### 2.3. Microstructure Analysis

The microstructure was examined in both the inner and the outer curvature regions of the deformed sheet using the electron backscatter diffraction (EBSD) technique. In the EBSD, the area and position with respect to the edge were kept constant for all conditions. The measurements were conducted  $\sim 100\ \mu\text{m}$  below the inner/outer surfaces of the formed/bent sample. This was done to avoid an uneven edge. The EBSD sample preparation was performed through standard mechanical grinding and polishing procedures, followed by a colloidal silica slurry polish. The EBSD maps were produced with a field emission LEO 1530 SEM instrument, equipped with HKL-CHANNEL 5, Oxford instruments operating at 20 kV and 8 nA current. The step size was either  $0.3\ \mu\text{m}$  or  $0.5\ \mu\text{m}$  depending on the microstructure characteristics. For each forming condition, multiple EBSD maps (up to 10 maps) were acquired to accommodate at least 230 grains, to ensure a statistically reliable measurement of the twin area fraction (TAF).

Since the initial material displayed a strong basal texture (Figure 4), the orientations observed away from the normal direction by  $50\text{--}90^\circ$  in the corresponding  $\{0001\}$  pole figure of the formed/bent material were considered as a twinned region using the sub-setting routine function in the HKL EBSD software, version 5.11.10405.0. Some regions of the matrix were wrongly identified as twinned areas and were manually changed to the untwinned matrix. The twin area fraction (TAF) was calculated by dividing the number of twinned area points by all data points.

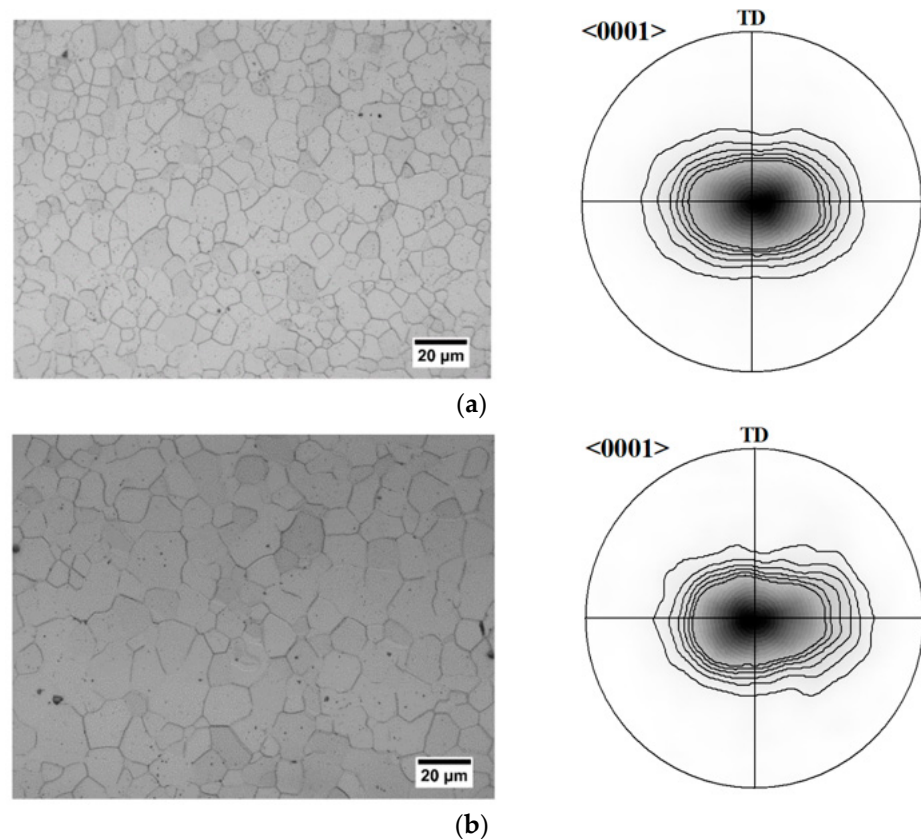


Figure 4. Cont.

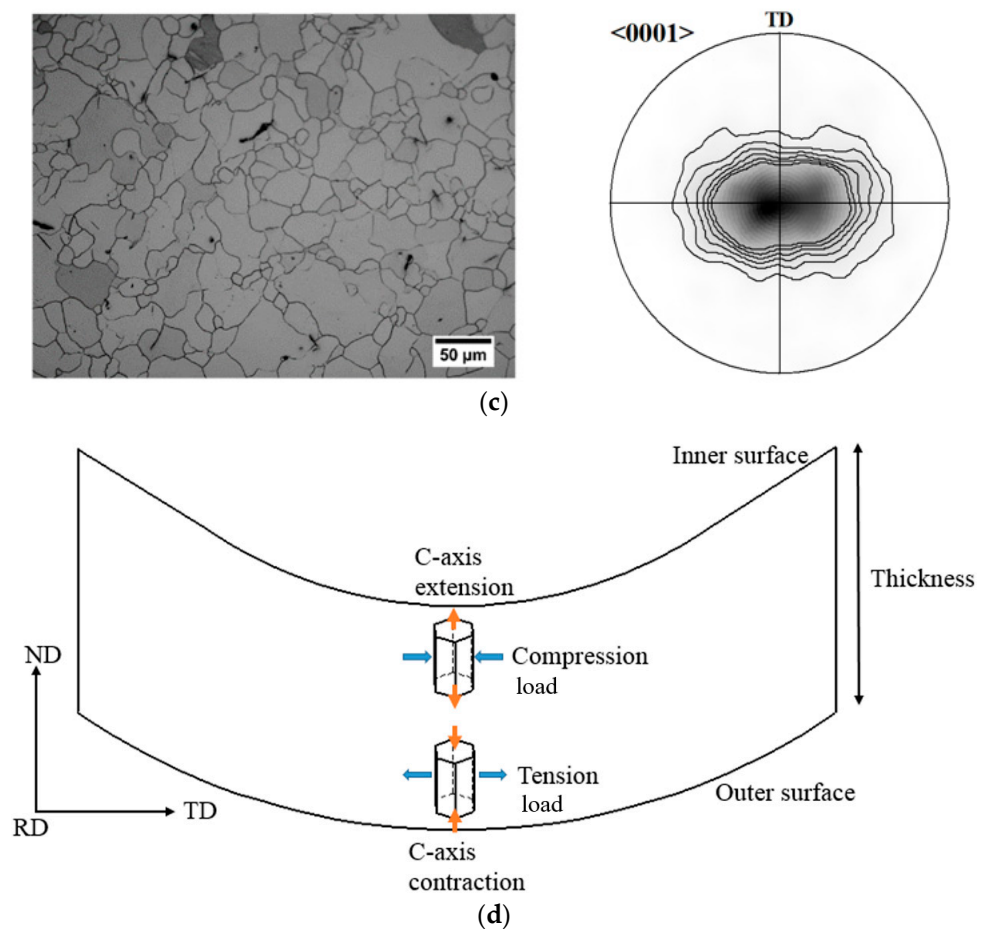


**Figure 4.** Optical micrograph of microstructures and their corresponding <0001> pole figures. (a) AZ31A annealed at 420 °C for 2 h to a grain size of 7 μm; (b) AZ31A annealed at 500 °C for 4 h to a grain size of 15 μm; (c) AZ31B with a grain size of 34 μm; (d) schematic representation of deformation modes at the inner and outer surfaces of magnesium upon bending with the C-axis perpendicular to the sheet surface. RD, ND and TD represent rolling, normal and transverse directions, respectively.

### 3. Results

#### 3.1. Microstructure

The microstructure of all magnesium alloys before bending deformation was analysed in a previous work [9] and consisted of equiaxed grains, free of any mechanical twins (Figure 4a–c). All conditions displayed a strong basal texture. As demonstrated in Figure 4d, the deformation mode alters at the inner and outer curvature surfaces of the material when in the bending process the C-axis orientation is perpendicular to the sheet surface. The inner surface experiences compression, which results in material extension parallel to the C-axis. The outer surface is subjected to tension, which leads to compression parallel to the C-axis. These regions are, therefore, termed bend “compression” and “tension” regions, respectively.

#### 3.2. Mechanical Properties

Note that in the following part of this work, the three material conditions will be referred to in form of their grain sizes and not their material specifications, i.e., grain sizes 7 and 15 μm correspond to AZ31A.

The mechanical properties of the material were analysed for all three conditions in a previous work [8]. This showed that all grain size conditions had very similar yield strength levels, combined with small differences in hardening behaviour at higher levels

of true strain. Up to a true strain of 0.06, the difference in material strength was found to be small.

### 3.3. The Springback Ratio (SBR) and Twinning Area Fraction (TAF)

For all conditions, the springback ratio was determined with Equation (5).

$$\text{Springback ratio} = \frac{\Delta\theta}{\theta_b} \quad (5)$$

with the springback and the bend angle under load,  $\Delta\theta$  and  $\theta_b$ , respectively.

In sheet metal bending, the maximum fibre strain occurs in the outer surface of the bend, and springback in bending generally decreases with increasing bending strain [22]. The springback results are therefore presented in combination with the true maximum outer fibre strain calculated with Equation (6) [22].

$$\text{True maximum outer fibre strain, } \varepsilon = \ln\left(1 + \frac{t}{2R}\right) \quad (6)$$

where  $t$  and  $R$  are the material thickness and the radius of curvature, respectively.

The springback ratios determined in the V-bend test are compared to those identified in the roll forming trials in Figure 5. In both the V-bending (Figure 5a) and the roll forming tests (Figure 5b), the springback ratio decreases with increasing grain size and outer bending strain level.

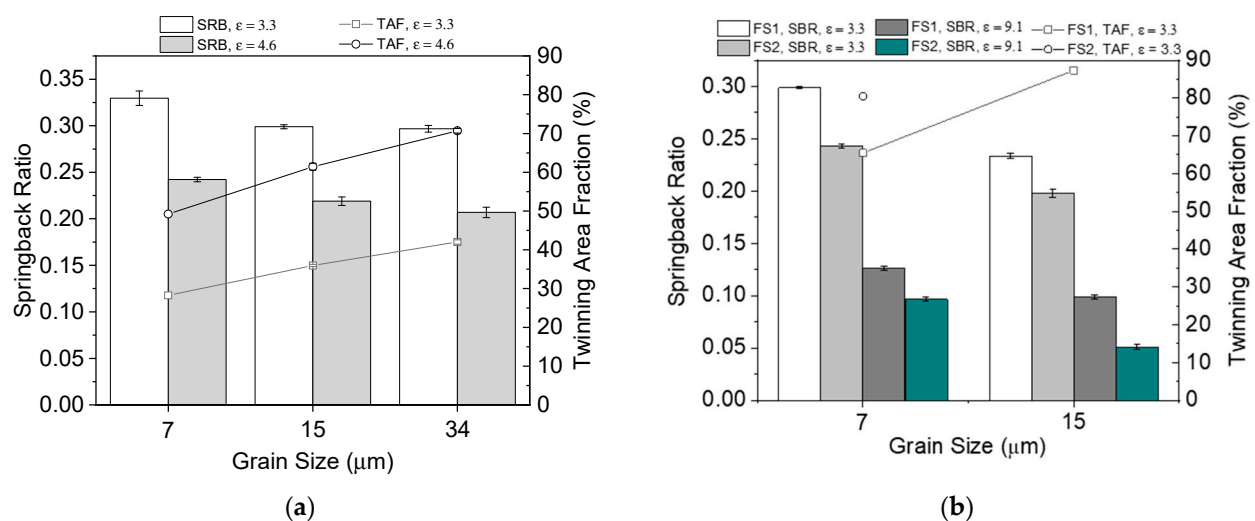


**Figure 5.** Springback ratio (SPR) and twinning area fraction (TAF) in the compression zone (a) V-bend test; (b) roll forming. AZ31A corresponds to grain sizes 7 and 15 μm, while AZ31B corresponds to 34 μm.

In roll forming, the springback ratio clearly depends on the forming sequence. When forming with FS1, the springback ratio is approximately 24% and 30% higher compared to FS2 for the 7 μm and the 15 μm grain size conditions (see Figure 5b), respectively. Comparison of the springback ratio for the same outer fibre strain of  $\varepsilon = 3.3\%$  shows that the springback is less in roll forming compared to the V-bend case, especially for FS2 (compare Figure 5a,b); for the FS2 condition, springback is approximately 30–34% lower for both grain sizes compared to the V-bend test for the same level of maximum outer fibre strain.

The twinning area fraction (TAF) is only shown for the compressive part of the bend radius, given that in the tension zone twinning was close to zero. In the V-bend test, the TAF increases with grain size and maximum outer fibre strain level (Figure 5a).

The same trend can be observed for the roll forming sequence FS1 (Figure 5b), where the TAF increases with a grain size augmented from 7  $\mu\text{m}$  to 15  $\mu\text{m}$  by approximately 33% for the  $\epsilon = 3.3\%$  condition. In comparison to this, the increase in TAF that occurs when the outer fibre strain is increased from  $\epsilon = 3.3\%$  to  $\epsilon = 9.1\%$  is much smaller and only 10% (compare TAF,  $\epsilon = 9.1\%$  with TAF,  $\epsilon = 3.3\%$  for the 7  $\mu\text{m}$  grain-size condition, Figure 5b). The TAF determined for FS2 is approximately 16% higher compared to FS1 (compare TAF,  $\epsilon = 3.3\%$ , for the 7  $\mu\text{m}$  grain-size condition in Figure 5b), while it is almost three times higher than the TAF observed in V-bending (compare TAF,  $\epsilon = 3.3\%$ , for the 7  $\mu\text{m}$  grain-size FS2 condition in Figure 5b with TAF,  $\epsilon = 3.3\%$ , for the 7  $\mu\text{m}$  grain-size in Figure 5a).

Note that in the channel bend test, the punch corner radius (PR) is 6 mm, giving  $\epsilon = 8.2\%$ , while the die corner radius (DR) is 4 mm,  $\epsilon = 11.8\%$ . Figure 6a shows that, like the V-bend and the roll forming case, springback also reduces with increasing grain size and outer fibre strain in channel bending, i.e., a lower springback was observed in the die corner,  $\epsilon = 11.8\%$ , in comparison to the punch corner,  $\epsilon = 8.2\%$ .

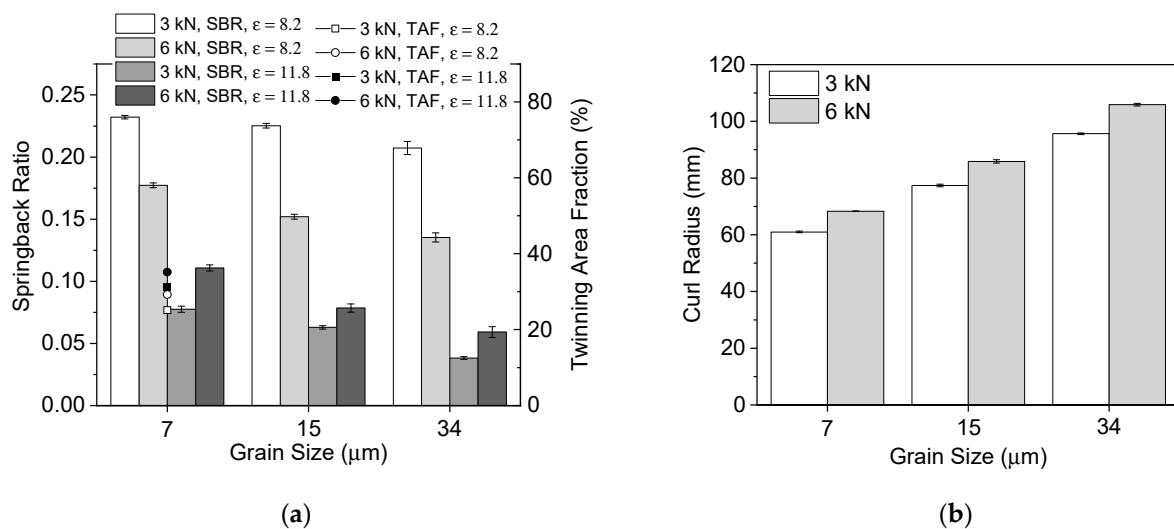


**Figure 6.** Springback and curl radius in the channel bend test as a fraction of the grain size and the blank holder force. (a) Springback ratio (SBR) and twinning area fraction (TAF); (b) side wall curl radius. AZ31A corresponds to grain sizes 7 and 15  $\mu\text{m}$ , while AZ31B corresponds to 34  $\mu\text{m}$ .

Increasing the blank holder force from 3 to 6 kN reduced springback in the punch corner radius, while there is a small increase in springback in the die corner radius in Figure 6a. The TAF was only measured for a grain size of 7  $\mu\text{m}$ . This showed an approximate increase of 12% in TAF between the punch radius (PR) and the die corner (DR) region, i.e., when the maximum outer fibre strain increased from  $\epsilon = 8.2\%$  to  $\epsilon = 11.8\%$  (compare hollow with full squares and hollow with full circles in Figure 6a). The TAF in both the PR and the DR regions slightly increased with an increasing BHF (compare hollow squares and hollow circles for  $\epsilon = 8.2\%$  and full squares with full circles for  $\epsilon = 11.8\%$  in Figure 6a).

The side wall curl radius increased with the grain size for all levels of blank holder force, see Figure 6b.

### 3.4. Twinning Behaviour—Twin Type and Area Fraction

In V-die bending, twinning was analysed for the two microstructures of 7  $\mu\text{m}$  and 15  $\mu\text{m}$  and the two final forming radii (i.e.,  $\epsilon = 3.3\%$  and  $\epsilon = 4.6\%$ ). In the compression region of the formed radius, the  $\{10\bar{1}2\}$  tension twin type was largely formed within the grains. In the tension region, other twin types such as  $\{10\bar{1}1\}$  and  $\{10\bar{1}5\}$  were identified, along with the  $\{10\bar{1}2\}$  tension twin type (see Figure 7). The extent of mechanical twinning was significantly higher in the compression region compared with the tension region for a given condition (i.e., grain size and strain, Figure 7). Increasing the grain size (compare

Figure 7a,b) and strain (compare Figure 7a,c) led to higher mechanical twinning in both the compression and the tension regions, as indicated by the increased TAFs.

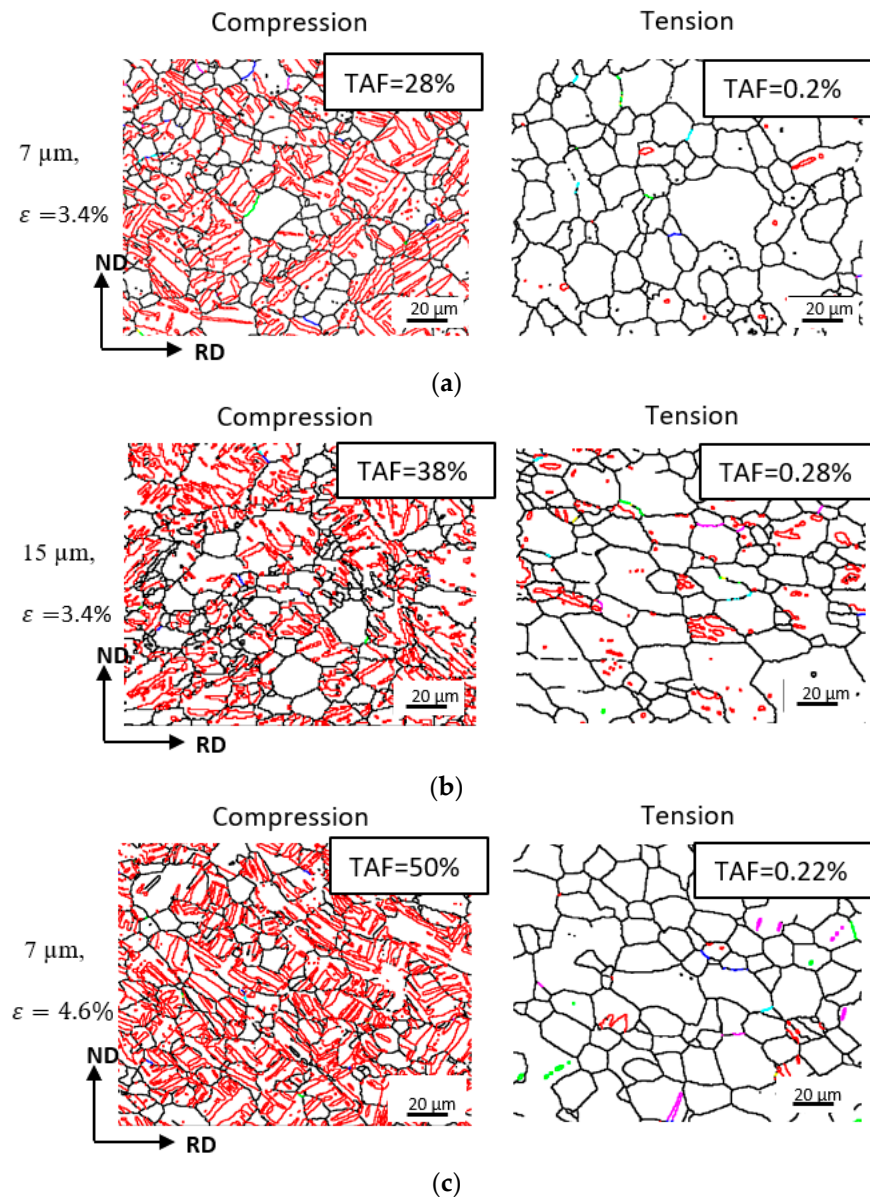


**Figure 7.** EBSD maps of AZ31A Mg sheet with different grain sizes subjected to V-bending at different maximum strains for compression and tension regions: (a) 7  $\mu\text{m}$ ,  $\epsilon = 3.4\%$ ; (b) 15  $\mu\text{m}$ ,  $\epsilon = 3.4\%$ ; (c) 7  $\mu\text{m}$ ,  $\epsilon = 4.6\%$ . Black, red, fuchsia and blue lines refer to high-angle boundaries and boundaries with lattice misorientation close to  $\{10\bar{1}2\}$  twin ( $86^\circ <1\bar{2}10>$ ),  $\{10\bar{1}1\}$  twin ( $56^\circ <1\bar{2}10>$ ) and  $\{10\bar{1}3\}$  twin ( $41^\circ <1\bar{2}10>$ ), respectively.

Figure 8 shows the twinning in the profile radius region for the two microstructures of 7  $\mu\text{m}$  and 15  $\mu\text{m}$  and the two forming sequences FS1 and FS2 for a maximum outer fibre strain of  $\epsilon = 3.3\%$ . The level of twinning increased significantly when changing the forming sequence from FS1 to FS2 (compare Figure 8a,b), while an even higher increase in TAF was observed when the grain size increased from 7 to 15  $\mu\text{m}$ .

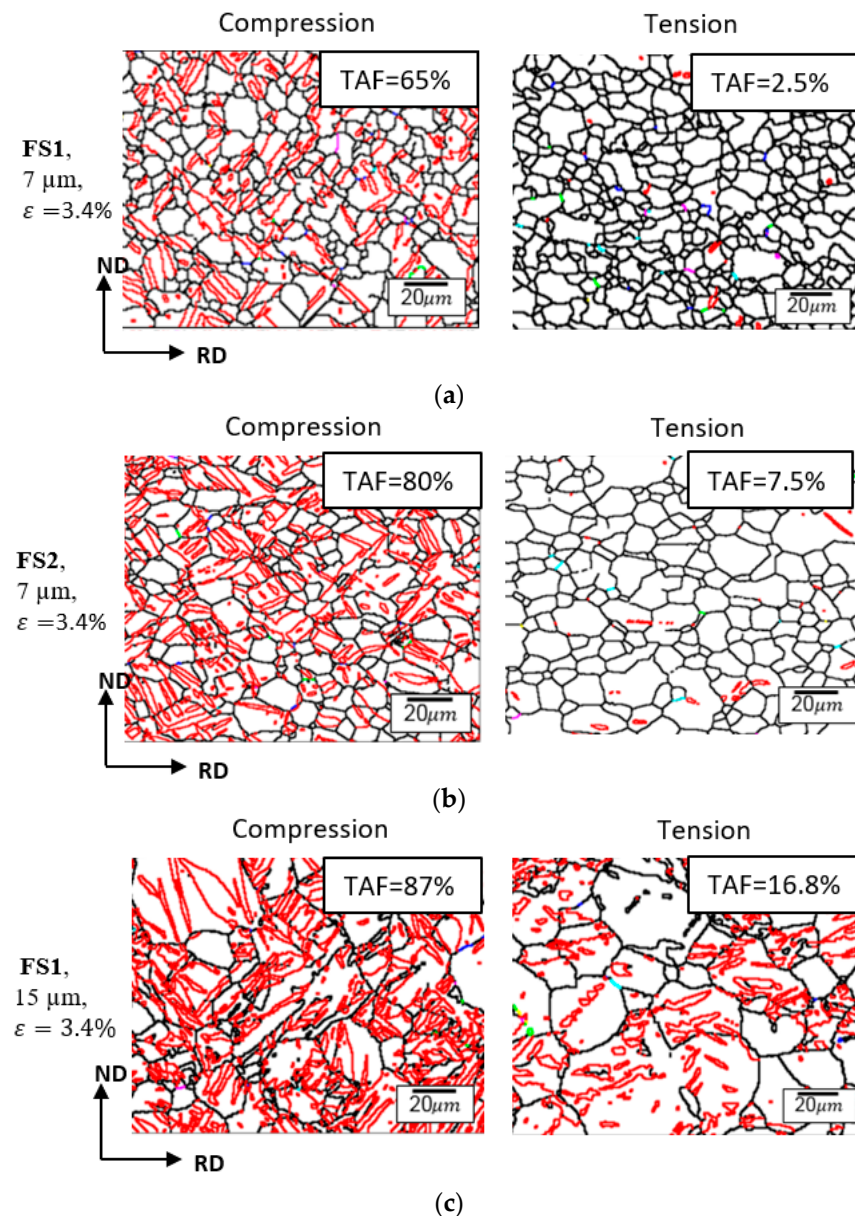


**Figure 8.** EBSD maps of AZ31A Mg sheet with different grain sizes subjected to roll forming with two different forming sequences, FS1 and FS2, and formed to a maximum outer fibre strain of  $\epsilon = 3.3\%$  for compression and tension regions. (a) FS1, 7  $\mu\text{m}$ ,  $\epsilon = 3.4\%$ ; (b) FS2, 7  $\mu\text{m}$ ,  $\epsilon = 3.4\%$ ; (c) FS1, 15  $\mu\text{m}$ ,  $\epsilon = 3.4\%$ . Black, red, fuchsia and blue lines refer to high-angle boundaries and boundaries with lattice misorientation close to  $\{10\bar{1}2\}$  twin ( $86^\circ <1\bar{2}10>$ ),  $\{10\bar{1}1\}$  twin ( $56^\circ <1\bar{2}10>$ ) and  $\{10\bar{1}3\}$  twin ( $41^\circ <1\bar{2}10>$ ), respectively.

Note that the amount of twinning is more than double, and almost triple, in roll forming compared to that observed in V-bending at the same maximum outer fibre strain ( $\epsilon = 3.3\%$ ) for the FS1 and the FS2 condition, respectively (compare Figure 8a,b with Figures 7a and 8c with Figure 8b). Moreover, it can be observed that the level of mechanical twinning in the tension region in roll forming was more than one order of magnitude higher than that observed in V-die bending (compare Figure 8a and Figure 8c with Figure 7a and Figure 7b, respectively).

The effect of the blank holder force in channel bending on the extent of microstructural changes in the punch corner, the side wall, and the die corner (as demonstrated schematically in Table 2), are shown for the 7  $\mu\text{m}$  grain size in Figures 9 and 10.

Mechanical twinning in the die and the punch corner was mostly observed in the compression zones (Figure 9a,b), while there were only a few twins in the tension regions. Twinning was low in the side wall in both the compression and tension zones (Figure 9c), with the twinning area fraction being nearly zero.

Mechanical twinning increased with the blank holder force for all positions and deformation modes. The blank holder force also influenced the twinning type that was formed at different sample positions. Applying a 3 kN blank holder force led to the formation of  $\{10\bar{1}2\}$  tension twins in both the compression and the tension regions of all positions (Figure 9), while at 6 kN, in addition to the  $\{10\bar{1}2\}$  tension twins,  $\{10\bar{1}1\}$  and  $\{10\bar{1}3\}$  compression twin types were observed in the tension regions of the die and the punch corner (Figure 10). Comparing Figures 9 and 10, it becomes clear that the increase in blank holder force only led to a minor increase in TAF for all test regions.

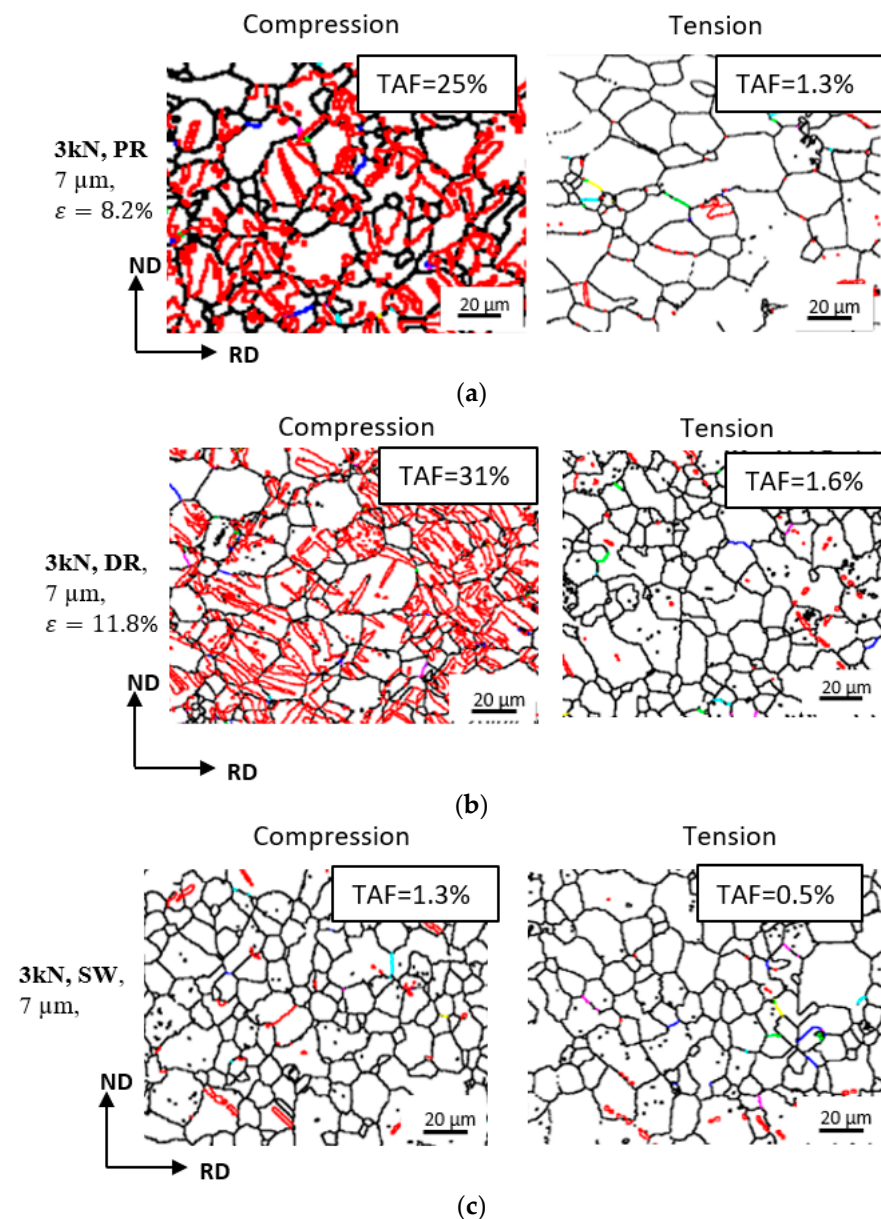


**Figure 9.** EBSD maps for grain size of 7  $\mu\text{m}$  AZ31A subjected to channel bending with 3 kN blank holder force: (a) punch radius (PR); (b) die radius (DR); (c) side wall (SW). Black, red, fuchsia and blue lines refer to high-angle boundaries and boundaries with lattice misorientation close to  $\{10\bar{1}2\}$  twin ( $86^\circ < \bar{1}210 >$ ),  $\{10\bar{1}1\}$  twin ( $56^\circ < \bar{1}210 >$ ) and  $\{10\bar{1}3\}$  twin ( $41^\circ < \bar{1}210 >$ ), respectively.

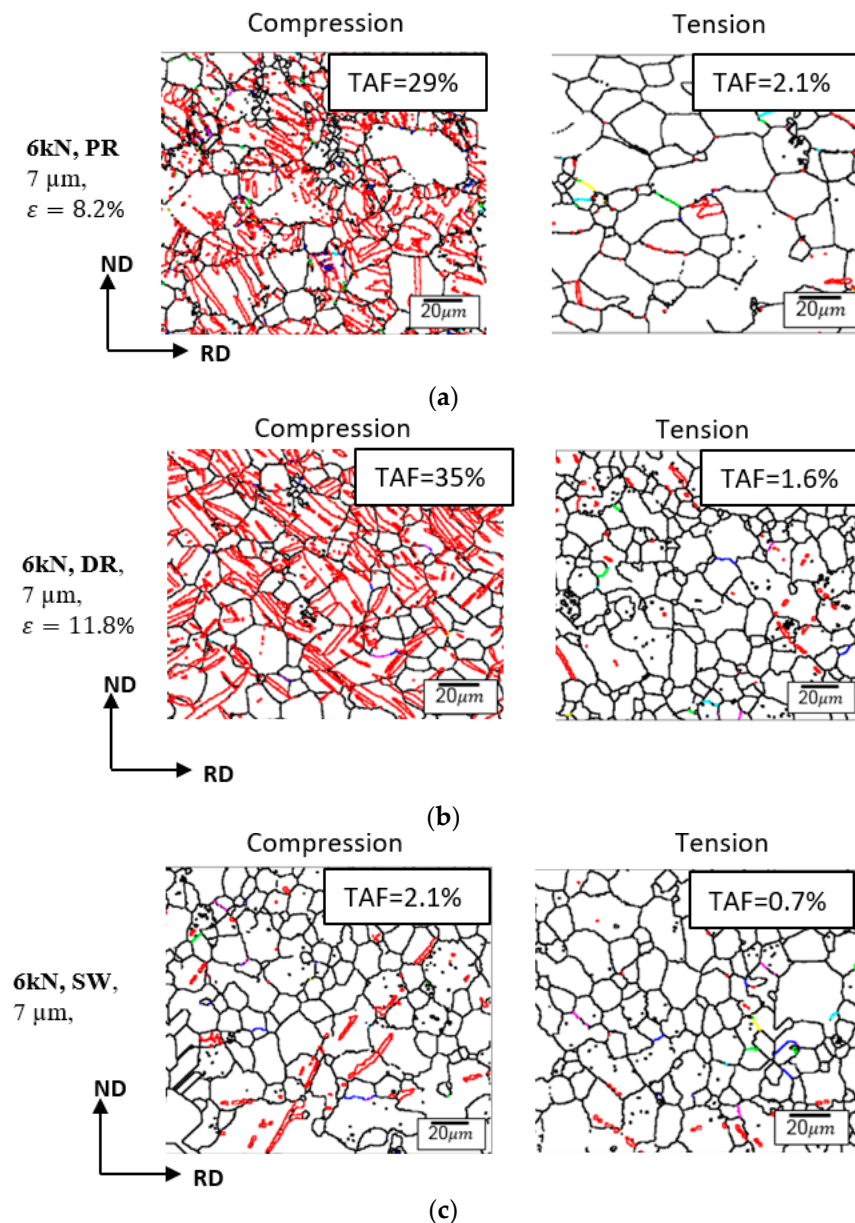


**Figure 10.** EBSD maps for grain size 7  $\mu\text{m}$  AZ31A Mg sheet subjected to channel bending with 6 kN blank holder force: (a) punch radius (PR); (b) die radius (DR); (c) side wall (SW). Black, red, fuchsia and blue lines refer to high-angle boundaries and boundaries with lattice misorientation close to  $\{10\bar{1}2\}$  twin ( $86^\circ <1\bar{2}10>$ ),  $\{10\bar{1}1\}$  twin ( $56^\circ <1\bar{2}10>$ ) and  $\{10\bar{1}3\}$  twin ( $41^\circ <1\bar{2}10>$ ), respectively.

#### 4. Discussion

The results of this work clearly show that deformation and mechanical twinning when bending magnesium sheet are influenced by the grain size, the level of applied strain and tension, as well as the forming mode, i.e., bending type and roll forming. There is also an inhomogeneous distribution of twinning throughout the material thickness.

##### 4.1. Twinning Inhomogeneity throughout the Sheet Thickness

As demonstrated schematically in Figure 4d, the deformation mode in bending changes throughout the thickness from tension (outer region) to compression (inner region), and this alters the mechanical twinning throughout the thickness. Mechanical twinning is a function of texture and the loading mode, i.e., compression or tension. If deformation leads to an extension along the C-axis of a grain, mechanical twinning occurs. This was previously shown by Huang et al. [4], where in a three-point bending of AZ31, the formation of

twinning was observed in the bending compression region, where the C-axis was subjected to extension. In contrast, in the tension region where the C-axis is contracted, non-basal slip systems are activated and mechanical twinning is negligible [4,10,23]. The current study shows a clear transition line between the twinned and the non-twinned regions in the compression and tension region, respectively, over the material thickness, Figure 11. There is some twinning in the sheet centre, which suggests that the neutral layer is shifted towards the tension zone. This has been confirmed by a DIC strain analysis performed in pure and V-die bending trials in previous work [9].

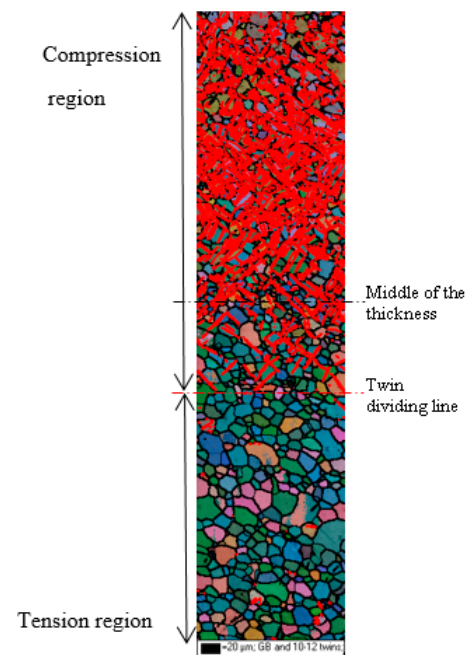


**Figure 11.** EBSD map with highlighted mechanical twin deformation through the thickness in an AZ31A sample bent to a 4.6% strain in the V-die bend test. Red refers to  $\{10\bar{1}2\}$  twin boundaries ( $86^\circ <1\bar{2}10>$ ). The sample grain size was  $7\ \mu\text{m}$ .

#### 4.2. The Effect of the Grain Size

It is well known that an increase in grain size decreases the critical resolved shear stress for mechanical twinning in magnesium [24,25] and twinning-induced plasticity (TWIP) steel [26]. In AZ31, the volume fraction of grains that contain at least one twin system increases with the initial grain size [24]. This is in accordance with the results of this study, where for all deformation modes a clear increase in TAF was observed with grain size (see Figures 5 and 6a,b) in the bend compression region, where the extension of the c-axis leads to mostly extension twinning [23].

#### 4.3. The Effect of Strain

In magnesium, the volume fraction of twins increases with the level of deformation [27–30], and this aligns well with the results obtained for bending and roll forming of this study. For example, in V-bending, an increase in the maximum outer fibre strain from 3.3% to 4.6% (i.e., a reduction in bend radius from 15 mm to 10 mm), which represents an overall increase in deformation of approximately 29%, increases the twin area fraction in the compression region from 28% to 50% (Figure 7) for the  $7\ \mu\text{m}$  condition; this is an overall TAF increase of 45% due to strain. Previous work has suggested that beyond a critical strain limit of 5%, the volume fraction of twins in AZ31 remains constant [28]. However, the channel drawing test results of this study suggest that the TAF can continue to increase with a forming strain beyond strains of 8.2%. In Figure 9, an increase in maximum outer fibre strain from 8.2% to 11.8% (punch corner PR vs the die corner DC radius) led to a TAF increase from 25% to 31%. This represents an overall TAF increase of 20% in the

bend compression zone for an overall strain increase of 31%. Therefore, it can be concluded that in bending magnesium, the TAF in the bend compression zone increases with the deformation level. Our study shows that at higher levels of strain, the rate of TAF increase slows down but does not seize.

#### 4.4. The Effect of the Bend Forming Mode

##### 4.4.1. The Twinning Area Fraction (TAF)

There is a clear effect of the forming mode on the twinning area fraction. The TAF produced in roll forming is more than 2 and 20 times that generated in V-bending in the compression and the tension zones, respectively, when forming  $\varepsilon = 3.3\%$  for the 7  $\mu\text{m}$  grain size (compare Figures 7 and 8a). This could be related to the longitudinal bending and unbending deformation that occurs when the material enters the forming rolls and that leads to an additional material deformation in the longitudinal direction. However, the TAF results shown in Figure 10c suggest that in a forming–unforming event, twinning and detwinning occur. In the channel drawing tests, this results in nearly zero TAF in both the tension and the compression zone of the channel wall. In contrast to channel bending, in roll forming the bending and restraughtening of material does not happen in the bending direction but occurs perpendicular to the bend axis, i.e., in the longitudinal and not the transverse direction [14]. Currently, it is unclear how this would have led to an increase in TAF, and further research is required. However, the results of this study provide clear evidence that the TAF is largely affected by the deformation mode and that even if the grain size and the forming strain level (the profile radius that is formed) remain the same, there can be a significant difference in the TAF. This is also confirmed when comparing the TAF of the FS1 and the FS2 condition in Figure 5. Even though the same profile radius and strain level of 15 mm and  $\varepsilon = 3.3\%$ , respectively, are formed for the 7  $\mu\text{m}$  grain-size condition, the TAF level of the FS2 condition is 20% higher compared to FS1. In FS2, a more severe bending sequence was applied, and based on previous observations this should have led to higher redundant deformation in the flange edge [21]. The TAF results suggest that the more severe FS2 bending sequence also affects the level of material deformation in the profile radius. This may be due to a more severe bending and restraughtening of material over the forming roll. Overall, the observations in bending and roll forming suggest that the TAF is not only affected by grain size and forming strain level but that the deformation mode also has a significant effect. This leads to significantly higher TAF levels in roll forming compared to bending.

##### 4.4.2. The Springback Ratio

It is well known that the springback ratio in sheet metal forming reduces with a decreasing forming radius, i.e., with an increasing maximum outer fibre strain,  $\varepsilon$  [22]. For bending magnesium, the same trend has been observed [29]. Previous work has further shown that a decrease in material strength via annealing [11], or forming at elevated strain rates [9], can also lead to a reduction in springback. Note that in the current study, the material strength was kept approximately the same between the 7 and the 15  $\mu\text{m}$  grain-size conditions [8]. Therefore, the trends observed regarding the change in springback ratio for these two grain-size conditions cannot be related to a change in yield strength. Other studies suggest that springback in bending magnesium is highly affected by the tension compression strength mismatch, which leads to a shift in neutral layer position towards the tension side in bending. If the grain size increases, mechanical twinning in the bend compression region is facilitated; this enhances the neutral layer shift and, in turn, reduces springback [8]. This suggests that an increase in TAF in the bending compression zone will result in a reduction in the springback ratio. This is confirmed in the V-bend and the roll forming test results shown in Figure 5, where an increase in maximum outer fibre strain and grain size led to a significant increase in the TAF and the reduction of the springback ratio. For the 7  $\mu\text{m}$  grain size, the TAF in roll forming is significantly higher compared to

V-bending for the same profile radius and outer fibre strain level. This leads to a lower springback in roll forming compared to V-bending.

To understand whether it is the TAF or the maximum outer fibre strain that mostly affects springback in bending magnesium, Figure 12a compares the relationship between the springback ratio (SBR) and the maximum outer fibre strain with that between the SBR and the TAF in Figure 12b. Note that the presented results are accumulated from the test results for the 7  $\mu\text{m}$  material condition determined in the pure bend (PB), the V bend (VB), the channel drawing (CD), and the roll forming process (RF).

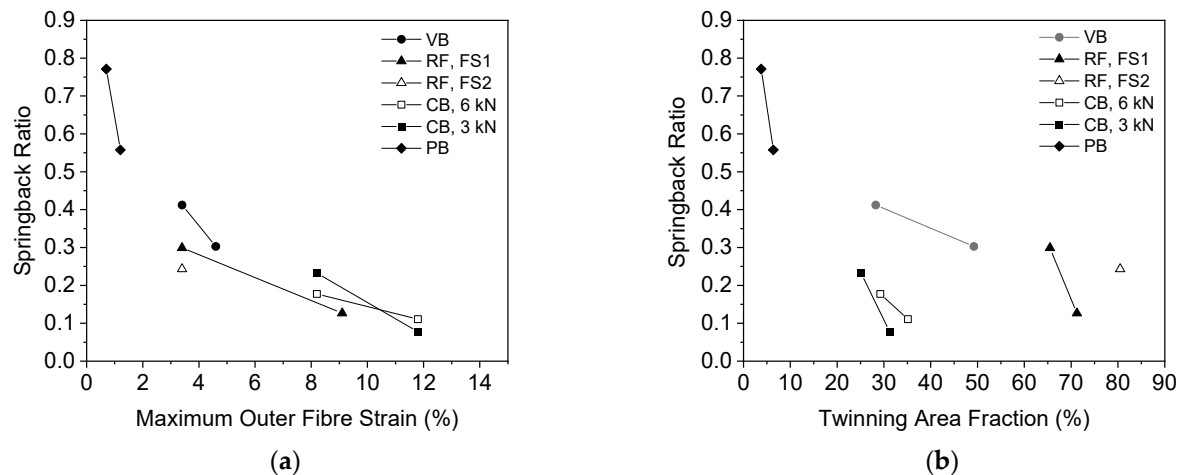


**Figure 12.** The springback ratio (SBR) as a function of (a) the maximum outer fibre strain and (b) the twinning area fraction (TAF).

Figure 12a clearly illustrates a reduction in the SBR with increasing maximum outer fibre strain. In contrast to this, the dependency of the SBR on the TAF is not that clearly defined. Comparing the RF-FS1 with the RF-FS2 case gives a higher SBR for RF-FS2, even though this condition has a significantly higher TAF compared to both RF-FS1 conditions. The same can be observed when comparing the VB with the CB conditions, where for the same TAF level of approximately 30%, the VB condition shows a significantly higher SBR compared to the CB condition. This suggests that the SBR in bending has a higher dependency on the maximum outer fibre strain that is formed than on the TAF. However, for some conditions, an increased TAF in the bend compression region is shown to give a significant reduction in the springback ratio.

#### 4.4.3. The Side Wall Curl in Drawing

The results of this study suggest that in channel drawing, the side wall curl in magnesium sheet increases with the grain size and the applied blank holder force. Previous work on conventional steel has revealed that the curl defect results from the bending and re-straightening of material over the profile radius when bending is combined with an applied tension. The applied tension leads to a shift in the neutral layer position, and this causes an inhomogeneous stress profile through the material [31]. The curl defect has been shown to decrease with material strength, given that this reduces the level of the residual stress [31], and this trend has been confirmed for AZ31 in heated channel bending tests [20]. In the current study, the grain size had no significant effect on the material strength of the three magnesium alloys tested [8]. The increase in side wall curl with the grain size therefore cannot be related to a change in the material strength. Figure 11 has revealed that a clear twin dividing line develops that is representative of the neutral layer position over the material thickness during bending. The twin dividing line is due to mechanical twinning that occurs in the compression bending zone where the C-axis is extended. The level of mechanical twinning that occurs in the compression bending zone increases with the grain size, and this leads to a higher shift in the position of the neutral layer. It therefore can be concluded that the increase in the curl defect with grain size is due to an enhanced neutral

layer shift towards the bending tension zone, which gives a more severe inhomogeneous stress profile.

#### 4.4.4. The Twinning Type

In V-bending, mostly  $\{10\bar{1}2\}$  extension-type twins were observed in the bend compression region. This is expected, given that here the C-axis is extended. The tension region mostly includes  $\{10\bar{1}1\}$  and  $\{10\bar{1}5\}$  compression twins, which are common twin types that form during the contraction of the C-axis [32]. However, there are also some  $\{10\bar{1}2\}$  type twins in the bend tension region. These may be related to twinning that is caused by the unloading and the resulting reversal in deformation, i.e., springback, which would extend the C-axis in the tension region. The TAF in the bend tension region is to an order of magnitude lower than that in the compression region.

In channel bending, the material experienced different strain profiles in the punch, the die corner and the side wall. In the punch and die corner, material undergoes deformation that is like V-bending but with an applied tension that acts perpendicular to the bend axis. The side wall experiences bending and unbending strains. Like in V-bending, in channel bending the  $\{10\bar{1}2\}$  tension twin type is mostly observed in the bend compression region, while in the tension region of the punch and the die corner there are only a few  $\{10\bar{1}1\}$  and  $\{10\bar{1}3\}$  compression twins that are accompanied with  $\{10\bar{1}2\}$  tension twins. The presence of compression twins in the tension region may be related to the tensile load that is induced by the blank holder force or may be the result of twins partly forming on unloading.

In roll forming, an incremental bending process takes place, but the final deformation is like that in V-die bending. In contrast to V-bending, in roll forming there is also material bending and unbending deformation in the longitudinal direction when the material enters and exits the forming roll [14]. Despite of this, only  $\{10\bar{1}2\}$  extension twins are observed in the compressive zone of the profile radius area for both the FS1 and FS2 conditions, i.e., the observed twinning types are the same as observed in V-die bending.

The above results suggest that there is only a small effect of the bending deformation mode on the twinning type formed in the tension and compression zones and that springback can lead to untwinning and the development of new twins in the tension/compression bending zones.

## 5. Conclusions

This study investigates the effect of forming strain and deformation mode on the twinning type, the twinning area fraction (TAF) and the springback ratio (SBR) in bending AZ31 magnesium. To control the level of material deformation, different bend forming radii were tested, while the deformation mode was varied by performing pure bending, V-bending, channel bending and roll forming trials. In channel bending and roll forming, different scenarios of applied blank holder force and bending sequence were analysed. Based on the current study, the following conclusions can be drawn:

- The TAF in bending magnesium sheet increased with the grain size and the maximum outer fibre strain. In contrast to previous work which suggests that the increase in TAF mostly occurs below a limit of 5% strain, this study has shown that even at strain levels that exceed 11%, the TAF keeps increasing with material deformation.
- The springback ratio in bending magnesium reduced with increasing outer fibre strain and an increasing TAF. However, the results of this work also suggest that for similar levels of TAF, the springback ratio can be significantly different. Overall, it can be concluded that springback in bending magnesium sheet is mostly affected by the forming strain level and to a lesser extent by the TAF.
- There is a clear effect of the forming mode on the TAF and springback. Especially in roll forming, the TAF level was significantly higher compared to that in simple V-bending even when the grain size, the bend radius and the maximum outer fibre strain were the same. There was also a clear effect of the incremental bending sequence on the TAF in roll forming. The higher TAF in roll forming might be due to the bending–

restraighening action that occurs in a longitudinal direction, i.e., perpendicular to the transverse bending direction, when material enters the forming rolls. The increased TAF in roll forming leads to a reduced springback ratio compared to the simple V-bending case.

- In contrast to roll forming, in channel bending, the bending and restraighening of the material over the die corner radius in the transverse bending direction leads to near zero TAF in the channel wall. This suggests that for some condition, the forming and reverse forming of material can cause twinning and detwinning, as was observed in some previous studies.
- Side wall curl in channel drawing increased with the grain size and was related to an increased shift in neutral layer position during bending leading to higher stress inhomogeneity through the material thickness.
- The type of the developed twins in the tension and the compression bending zones was not significantly affected by the bend forming mode, i.e., the same types of twins were identified in V-die and channel bending as well as in the roll forming process. In the tension region, some extension twins were observed, which suggests that springback in bending magnesium can lead to detwinning and/or the generation of new twins.

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