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Towards directly formable thin gauge AZ31 Mg alloy sheet production by melt conditioned twin roll casting

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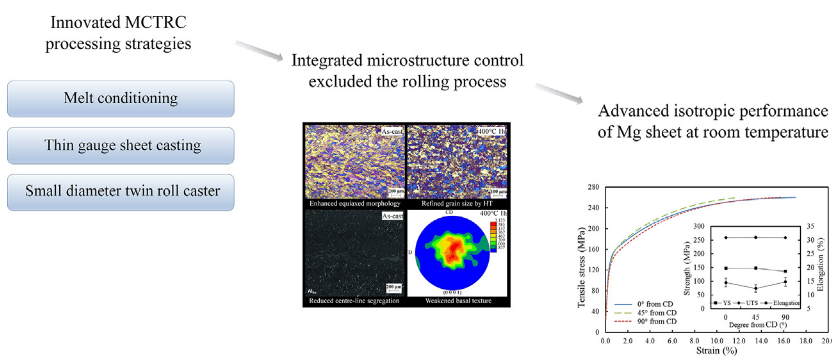
HIGHLIGHTS

- A novel solidification controlled twin roll casting strategy is developed.
- Thin AZ31 Mg alloy sheets are produced with uniform and equiaxed grains and highly reduced centre-line segregations.
- Homogenized Mg sheet showed mechanical properties comparable to those produced by conventional TRC and downstream processing.
- The excellent in-plane isotropy of tensile performance indicates high formability potential of homogenized Mg alloy sheets.

GRAPHICAL ABSTRACT



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ABSTRACT

A novel melt conditioned twin roll casting (MCTRC) strategy with emphasis on solidification control has been investigated for producing thin gauge Mg alloy sheets ready for component forming, with the minimal requirement of down-stream processing. The performance of 1.5 mm thick AZ31 Mg alloy sheet is reported in this study to demonstrate the effect of the solidification control strategy on the microstructure and mechanical properties of the Mg alloy sheet produced by MCTRC process. The anisotropy of in-plane tensile properties of the AZ31 sheets is evaluated in association with characteristic features of solidification, deformation behaviour and texture evolution during the solidification control MCTRC process. The improved mechanical performance is attributed to the refined and uniform microstructure, reduced centre-line segregation and minimized deformation, which results in a weak basal texture.

1. Introduction

There has been a strong demand for commercially viable technologies for Mg alloy sheet production from 3C (Computer, Communication and Consumer Electronic) and automobile industries, driven by the fast-growing Asian economy and the pursuit for low carbon, strong and lightweight structures. A focal point is for housing laptop computers, digital cameras and mobile phones where sheet stamping is seen to have advantages in productivity, structural diversity and product functionality over the currently used die casting [1,2].

In general, sheet materials and extrusion profiles represent the key area where the majority of weight savings may be made. Mg alloy sheets are conventionally produced through a manufacturing route consisting of slab casting and multiple passes of hot rolling and cold rolling rout involving numerous intermediate heat treatments [3]. This

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route suffers from low efficiency, high cost and high energy consumption. Twin roll casting (TRC) produces sheet directly from the melt by combining solidification and rolling into single operation through two metallic counter-rotating rolls, providing a substantially shortened manufacturing route for Mg alloy sheet production. The thickness of Mg alloy sheets produced by TRC is normally in the range of 5 to 8 mm, which is significantly smaller than that of casting slabs [4–6], offering benefits of a reduced number of rolling passes and heat treatments and reduced energy consumption [7].

A schematic illustration of the TRC process is presented in Fig. 1. The solidification of liquid metal usually begins at the two water cooled rolls near the meniscus region. Two solid shells then form from each roll and grow as the melt flows through the roll gap. These two solid shells congregate at the centre of the roll gap and thus the sheet is formed and shown as the solid zone (S) in the figure. The solidified metal undergoes thickness reduction upon rolling as it moves forward and reaches its final thickness at the roll nip (deformation region). The distance between the tundish tip and roll nip is the tip setback. In front of the solid zone, there is a semi-solid mushy zone where liquid (L) and solid (S) phases coexist. The initial liquid phase region and semi-solid region together are termed as the sump and the sump depth is determined by the TRC conditions, reflecting the solidification kinetics.

In the conventional magnesium alloy TRC process adapted from aluminium TRC technology, in which roll diameter is normally larger than 500 mm [8,9], a large amount of plastic deformation is applied in order to maintain good dimension and crown control in the as-cast strip [10]. Plastic deformation helps control the accuracy of sheet thickness and improves surface finish. The stored energy due to plastic deformation provides the driving force for recovery and recrystallization in the downstream homogenization treatment. However, large deformation leads to a high separation force and roll bending inevitably occurs, which requires supporting rolls to overcome or minimize roll bending. As a result, the TRC equipment becomes heavy, complicated and difficult to operate, with high energy consumption and high operation cost. At the meantime, with the high cooling rate and large thermal gradient, as-cast TRC sheets suffer from central line segregation due to the directional columnar growth from the surface to centre during solidification [11,12]. This macroscale chemical segregation deteriorates the quality of material and homogenization treatment is required to dissolve solute-rich phases into the matrix at a high temperature for a long period of time. In order to modify the as-cast microstructure suitable for final shape forming, as-cast sheets with an excessive thickness have to be produced to allow a dimensional window for downstream deformation.

For ductile metals such as steel and aluminium, to which the TRC process was initially applied [3,10,13], downstream rolling can be readily conducted to the required thickness and effectively breaks down the coarse and heterogeneous as-cast grain structures, producing sheets with a uniform chemical distribution and microstructure ready for component forming. However, extensive downstream rolling is not feasible for Mg alloy. This is because Mg with a close-packed hexagonal (hcp) crystal structure doesn't have a sufficient number of slip systems to accommodate deformation [2] and the rolling operation is difficult and costly. More critically, excessive rolling leads to the development of an intensified basal texture, which results in low ductility and strong anisotropy as described in previous research [14], jeopardizing the formability of the material for further forming.

In the present investigation, an alternative TRC process is developed with the emphasis on solidification control in order to obtain a uniform and equiaxed grain structure with minimized macroscopic chemical segregations so that it is possible to substantially shorten downstream thermomechanical processing and impede extensive development of the associated crystallographic textures.

The game change strategy in our solidification control approach is to employ intensive shearing melt conditioning immediately prior to TRC, termed as MCTRC, to improve nucleation kinetics and promote equiaxed growth. According to Hunt's model for columnar to equiaxed growth transition [15], number density of heterogeneous nucleation sites and the undercooling for nucleation are the two key factors influence the formation of an equiaxed grain structure for the solidified melt. Melt conditioning (MC) by intensive shearing technology developed at BCAST has demonstrated the capacity of grain refinement and defect control in a range of Mg alloys by improving nucleation kinetics through a twin-screw [16] or rotor-stator mechanism [17]. In Mg alloys, magnesium oxide (MgO) films inherent from Mg alloy ingot act as agents for heterogeneous nucleation. These MgO films are normally in coarse clusters and aggregate locally in the melt. Detailed investigations showed that intensive shearing breaks down these MgO films into discrete sub-micron particles and disperses them evenly throughout the melt [18]. The number density of available MgO nucleation sites can increase by three orders of magnitude after intensive melt shearing [19]. The development of a uniform, fine and equiaxed grain structure is expected to improve chemical homogeneity as solute-rich structures tend to be retained in the local inter-dendritic regions in such a grain structure, instead of being pushed into the centre area.

Another strategy in our approach is to produce Mg alloy sheets with a thickness close to that suitable for stamping. The feasibility of this strategy is based on the formation of a uniform, fine and equiaxed grain structure due to the employment of intensive shearing melt conditioning. Such a grain structure can obtain a status free of defects and chemical segregations by a simple thermomechanical processing

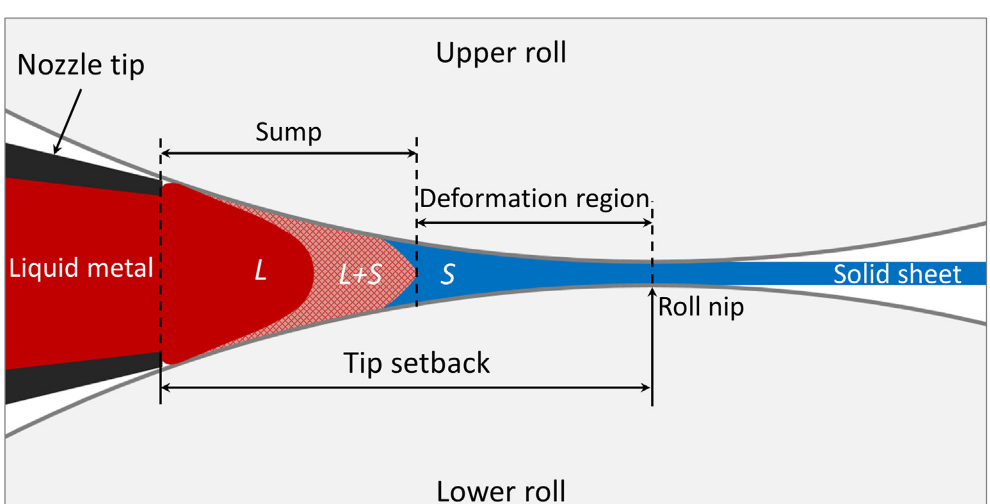

Fig. 1. Schematic diagram of twin roll casting process, showing regions of liquid, semi-solid and solid phases and the location of tip setback including sump and deformation region.

scheme with limited plastic deformation. Such Mg alloy sheets possess weak textures and most likely good formability. Thin sheet production by TRC is cost-effective as it is often associated with high speed and low force, in addition to substantially reduced downstream processing.

The third strategy integrated into this research is using small diameter twin roll caster to reduce the deformation in the TRC process. For processing sheets with a certain thickness, a small roll diameter provides a large opening for a tundish tip to move closer to roll nip. Consequently, the tip setback decreases and the plastic deformation zone is shortened [19,20]. Moreover, a small roll improves cooling efficiency due to the reduced overall heat capacity of the system, which enables a higher casting speed and thinner sheets to be processed. The use of small rolls thus helps the implementation of the strategy that targets thin gauge Mg alloy sheets with a low force and potentially high productivity. Certainly, the use of small rolls will restrict the width of the processed sheets to a certain value. However, the production of relatively narrow Mg alloy sheets is economically and commercially viable for applications in the 3C industry, which is the target market for the present research.

In summary, the present research aims to develop a novel twin roll technology, MCTRC process, for producing directly formable Mg alloy sheets by employing three unique strategies, i.e., melt conditioning treatment, near-to-net gauge thin sheet as target product and the use of small scale twin roll caster.

2. Experimental procedure

2.1. Solidification controlled MCTRC process

AZ31 alloy melt (Mg-3.29Al-1.02Zn-0.39Mn (in wt%)) was conditioned using a twin-screw high shear mechanism at 800 rpm for 1 min and then was immediately cast into 1.5 ± 0.1 mm thick sheet with 100 ± 10 mm width using an in-house-built horizontal twin roll caster at a pouring temperature of 650 °C and casting speed of 5 m/min. The in-house-built twin roll caster consists two counter rotating rolls with 110 mm in diameter with a working width of 150 mm which driven by two 15 kW motors. The experimental setup and produced AZ31 alloy sheet are presented in Fig. 1. The setback length between tundish tip and roll nip was 20 mm. The whole process was conducted under the protection of a mixed gas of 0.42% SF_6 in N_2 [21]. The AZ31 alloy sheets produced with the application of intensive shearing are referred to as MCTRC sheets hereafter. Some as-cast sheets were homogenized at 400 °C for 1 h, then air-cooled (Fig. 2).

2.2. Microstructure characterisation

Samples for microstructural characterisation were taken along the longitudinal section (TD plane) through the middle of both as-cast and homogenized MCTRC AZ31 sheets. Metallurgical samples were prepared using standard methods, with a final polishing with ethanol-based colloidal silica suspension. For grain size measurement, an acetic-picral solution (4.2 g picric acid, 15 ml acetic acid, 70 ml ethanol and 15 ml distilled water) was used. The microscopic observations were performed under normal and polarised light on a Carl Zeiss AxioScope A1 optical microscope and the liner intercept method was used for grain size measurement following ASTM E1382. Five fields were taken for grain size measurement and each field covering about 200 grains on average. For EBSD examination, the sheet samples were electropolished in a solution of 15% nitric acid in methanol at −30 °C and 12 V for 30 s. The samples were then immediately observed on a Zeiss Supra-35 SEM which is equipped with EDAX EBSD and EDS systems. EBSD maps for microstructure and texture analysis were obtained

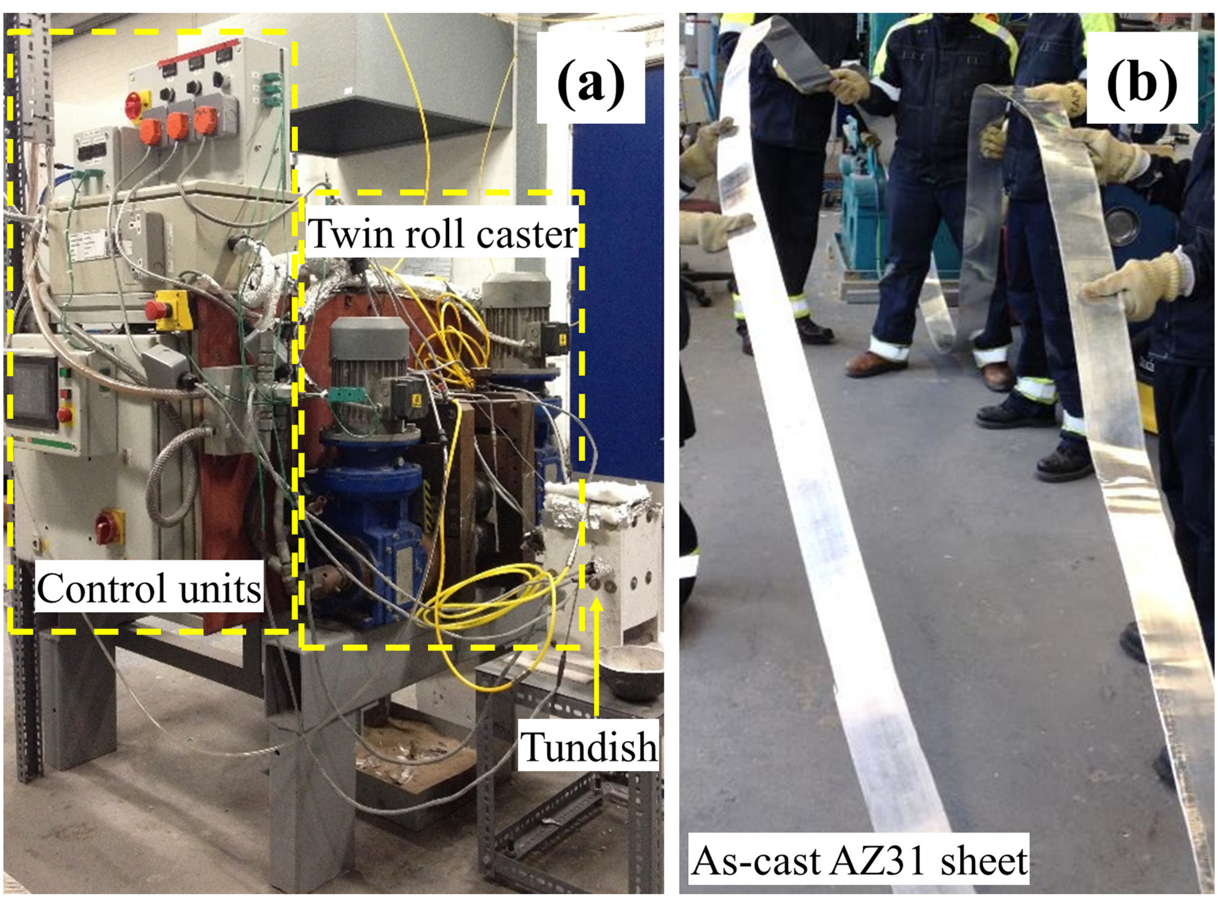

Fig. 2. Images of experimental setup of the in-house built horizontal twin roll caster (a) and the as-cast AZ31 alloy sheet (b).

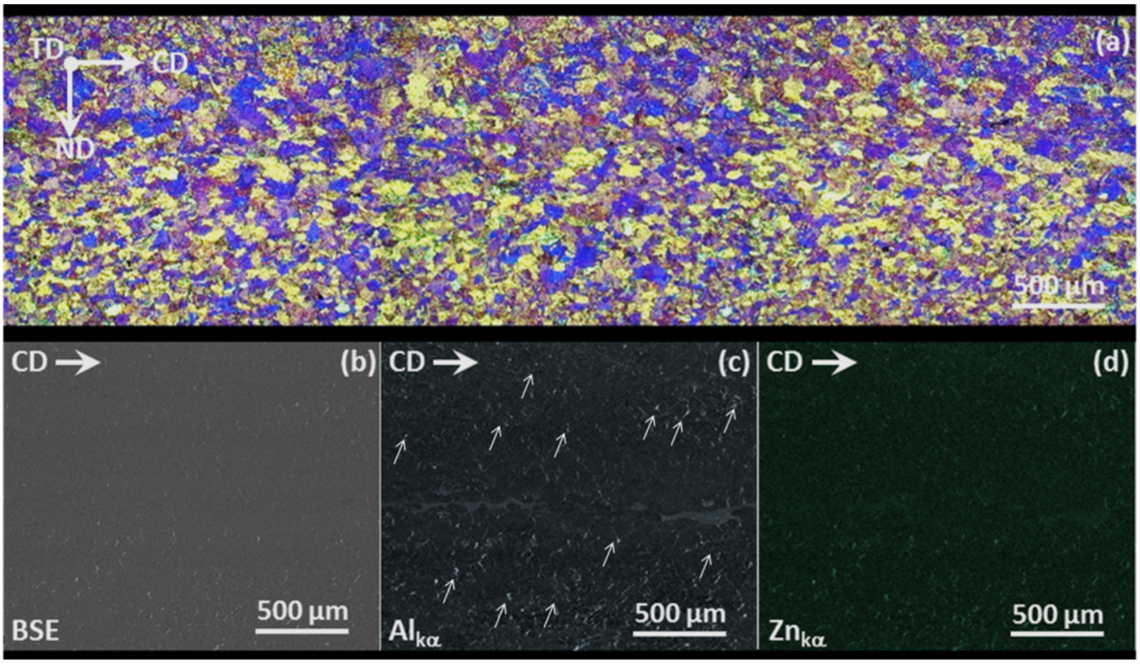

Fig. 3. The microstructure obtained from the longitudinal section of MCTRC sheets: (a) polarised micrograph, (b) BSE SEM image, (c) Al and (d) Zn element EDS maps.

from an area of 1.6 (CD) × 1.3 (ND) mm (which essentially covers the entire sheet thickness) at a step size of 1 μm. The EBSD data were analysed with the EDAX OIM™ software. Texture components and their maximum intensity and volume fraction were measured from the EBSD data with a tolerance of ±15° of the ideal orientation. The Schmid factor analysis on selected orientation is based on the stress state of uniaxial tension in CD, 45° and TD directions.

2.3. Mechanical properties test

Three samples along three in-plane directions, i.e., the casting direction (CD), the direction at 45° to the casting direction (45°) and the transverse direction (TD) were machined from the as-cast and homogenized MCTRC sheets according to the ASTM B557 standard with a gauge length of 25.00 ± 0.10 mm. The tensile properties were measured on an Instron 5500 Universal mechanical Testing System equipped with Bluehill software and a ±50 kN load cell. The Model 3542 extensometer with 25 mm gauge length is provided by Epsilon Technology Corp. The constant crosshead speed was 1 mm/min (6.5 $\times 10^{-4}$ s^{-1} initial strain rate). All the tensile tests described above were held at ambient temperature (~24 °C).

3. Results and discussions

The thin gauge AZ31 Mg alloy sheets produced were characterised by a uniform, fine and equiaxed grain structure, homogeneous chemical

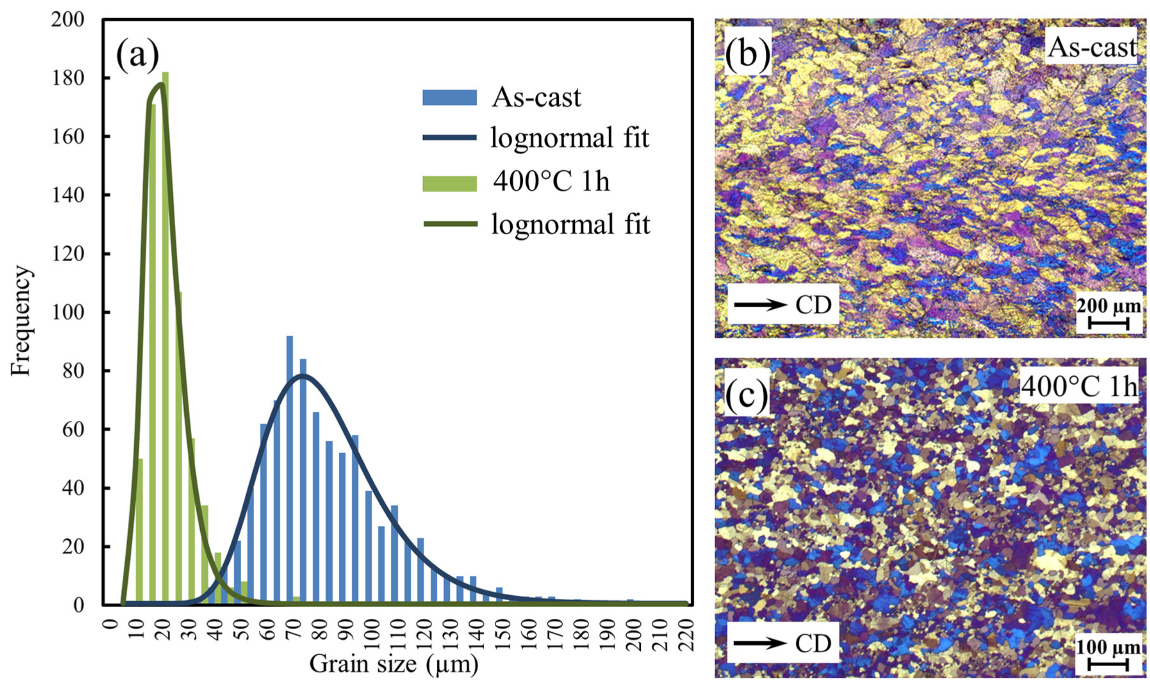

Fig. 4. The grain size distribution of AZ31 alloy sheets produced by MCTRC process (a), the microstructure of as-cast sample (b), and sample homogenized at 400 °C for 1 h (c).

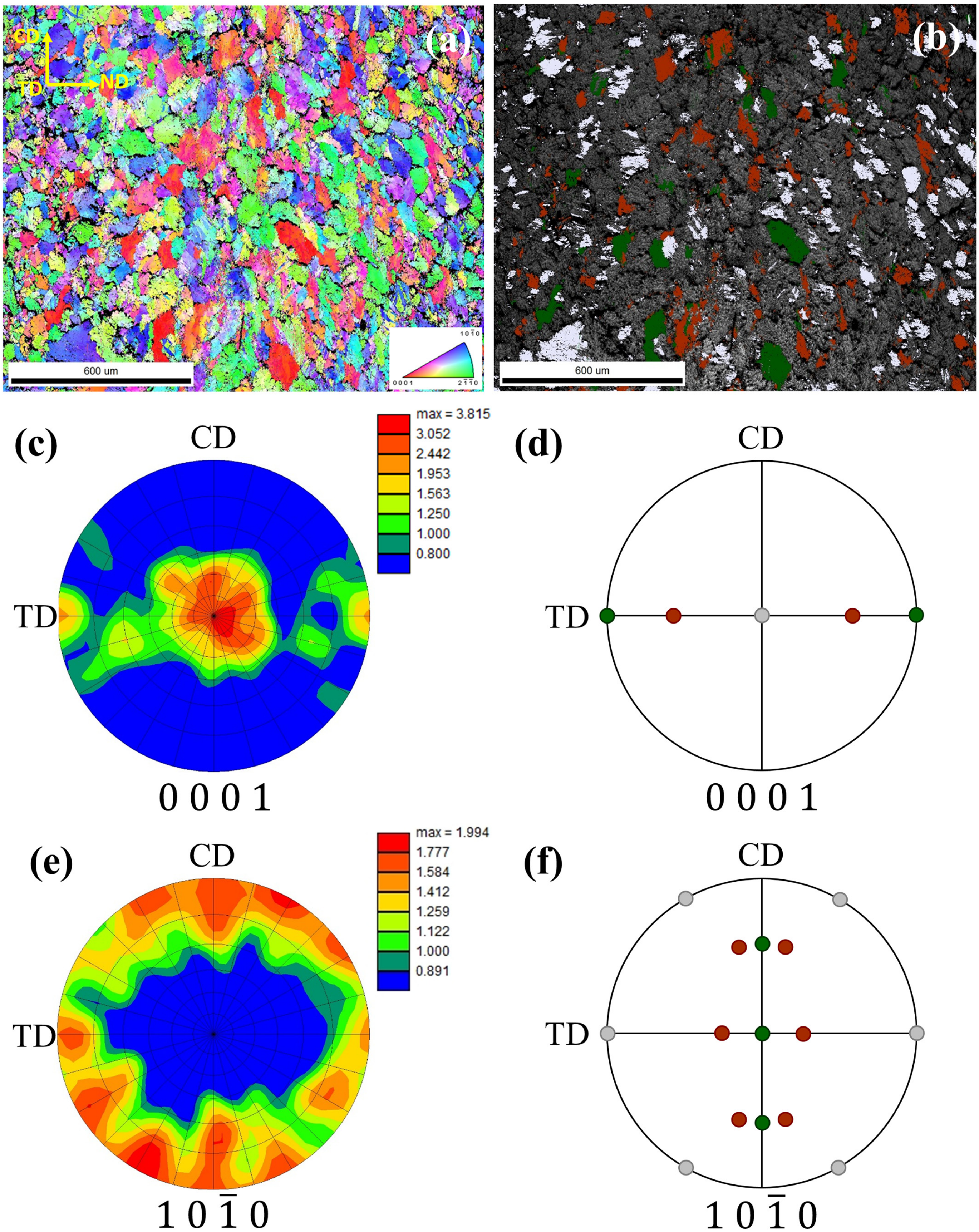

Fig. 5. Crystallographic textures of as-cast MCTRC sheets: (a) Inverse pole figure EBSD map, (b) highlighted grains of individual texture components, and (c) and (e) are {0001} and {10$\bar{1}$0} pole figure from EBSD data, (d) and (f) are theoretical poles of basal, {1$\bar{1}$00}⟨11$\bar{2}$0⟩ and {1$\bar{1}$01}⟨11$\bar{2}$0⟩ texture components respectively.

distribution and substantially reduced centre-line segregations. The overall texture was essentially randomised with a weak basal component. The MCTRC AZ31 alloy sheets were carefully examined and characterised by microstructure and texture analysis and mechanical testing. Detailed results are presented below.

3.1. Microstructure, chemical homogeneity and texture

The microstructure and chemical distribution of as-cast MCTRC AZ31 alloy sheets are presented in Fig. 3. Fine and equiaxed grains with a uniform size distribution are seen through the thickness. Meanwhile, the centre-line segregations were barely detected under the polarised light (Fig. 3(a)).

Backscattered electron (BSE) image (Fig. 3(b)) and EDS maps (Fig. 3 (c) and (d)) shown the distribution of solute elements Al and Zn through the sheet thickness. Aluminium element is seen in fine clusters of <20 μm, as indicated by white arrows in Fig. 3(c), and distributed uniformly in the matrix. In the centre area, discontinuous patches of bright contrast with a thickness of 37.5 ± 15.7 μm are presented. As a minor solute element, the EDS map of Zn in Fig. 3(d) shows a uniform distribution. The size of solute-rich patches in MCTRC sheet is significantly decreased compared to those millimetre sized centre-line segregations formed in AZ31 alloy sheet by conventional TRC [22–25].

The average rolling reduction of as-cast AZ31 alloy sheet via MCTRC process can be approximated geometrically by the difference in aspect ratios between ideal equiaxed grain and the measured value of as-cast grain morphology in MCTRC sheet based on the constant volume assumption of plastic deformation. The average aspect ratio of MCTRC sheet was measured to be 1.35 ± 0.32, while the value of ideal equiaxed morphology was 1.00. Thus, rolling reduction of AZ31 sheet by MCTRC process was estimated to be 14.70 ± 8.61% in this study, which is smaller than the value of 30–60% reported for a conventional TRC process [26]. Both reduced deformation and equiaxed growth controlled solidification contributed to the uniform distribution of solute elements as the solute-rich liquid was largely maintained in the local interdendritic regions during the solidification.

The grain size distribution of MCTRC AZ31 alloy sheets is presented in Fig. 4. The representative microstructure of as-cast and homogenized AZ31 sheets produced by MCTRC process are shown in Fig. 4(b) & (c). In as-cast condition, grains are of an equiaxed morphology with an average diameter of 83 ± 26 μm, which is much finer than the grain size ranging from 250 μm to 600 μm reported for the conventional TRC process [22,27–30]. The significant grain refinement is attributed to the enhanced heterogeneous nucleation by the dispersed MgO particle through melt conditioning treatment prior to casting [31]. After homogenization treatment at 400 °C for 1 h, the grain size further reduced to 15 ± 9 μm due to recrystallization, which is driven by the deformation induced stored energy. According to the study on the effect of melt condition treatment on Mg sheet homogenization [32], the refined microstructure and reduced secondary dendritic arm spacing (SDAS) of the AZ31 alloy sheet increase homogenization rate and accelerates static recrystallization. The uniform grain structure is considered to have improved the spatial distribution of stored energies due to plastic deformation and led to the formation of a finer grain structure after homogenization. Such a grain size is equivalent to that achievable for AZ31 sheets produced by conventional TRC plus multi-passes rolling with 60–80% reduction in thickness [24,25,33,34].

The conventional TRC with sequence rolling process is commonly criticised as limiting the sheet ductility due to highly intensified basal texture. It is therefore of great interest to examine the crystallographic texture characteristics of the MCTRC AZ31 thin sheets without downstream rolling process.

The orientation contrast map and related {0001} and $\{10\bar{1}0\}$ pole figures for the as-cast MCTRC AZ31 sheets are presented in Fig. 5(a), (c) and (e). The corresponding grains of major texture components are marked in a band contrast map in Fig. 5(b) and their poles are shown in Fig. 5(d) and (f) with a different colour code from that used in the orientation map in Fig. 5(a). The detailed information of texture components is given in Table 1.

Table 1
Maximum intensity and volume fraction of texture components. The colour code is used in Fig. 4(b).

Colour code	Component	Intensity	Volume fraction
	$\{0002\}\langle 11\bar{2}0\rangle$	3.27	10.3%
	$\{1\bar{1}00\}\langle 11\bar{2}0\rangle$	2.11	4.2%
	$\{1\bar{1}01\}\langle 11\bar{2}0\rangle$	1.17	6.5%

Besides the basal component, $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ and $\{1\bar{1}01\}\langle 11\bar{2}0\rangle$ components were also obtained with weak intensities as shown in Fig. 5(b). The $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ component could be caused by either the operation of the prismatic $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ slip system or $\{10\bar{1}2\}$ twinning [35–37]. By crystallographic feature analysis together with morphology examination, the majority of the component represents the prismatic slip system as shown in Fig. 5(d) and (f). Some of the laminar shaped structure is confirmed as $\{10\bar{1}2\}$ tension twinning by orientation relationship analysis [38]. Uniform spatial distribution of grains representing such orientation is observed in Fig. 5(b). The total volume fraction of $\{1\bar{1}00\}\langle 11\bar{2}0\rangle$ and $\{1\bar{1}01\}\langle 11\bar{2}0\rangle$ components was over 10%, which is comparable to that of the basal component.

Although the basal texture is dominant on the pole figure, its volume fraction within ±15° of ideal orientation was just ~10.3% and the corresponding grains were evenly distributed over the material volume. The appearance of non-basal $\langle a\rangle$ slips was considered to have provided extra deformation modes and basal texture development was limited [14]. The fine and uniform grain and weak basal texture developed in the solidification controlled MCTCR process are expected to have good mechanical properties and formability.

As expected, {0001} basal texture dominated in the as-cast MCTRC sheet. However, the texture intensity of 3.27 is very much moderate and the orientation is extensively spread around the basal peak over a half width of ~25°.

3.2. Mechanical performance

One of the key targets of this research is to reduce the prolonged downstream processing after TRC. In the present work, the MCTRC AZ31 sheets were only homogenized at 400 °C for 1 h and their

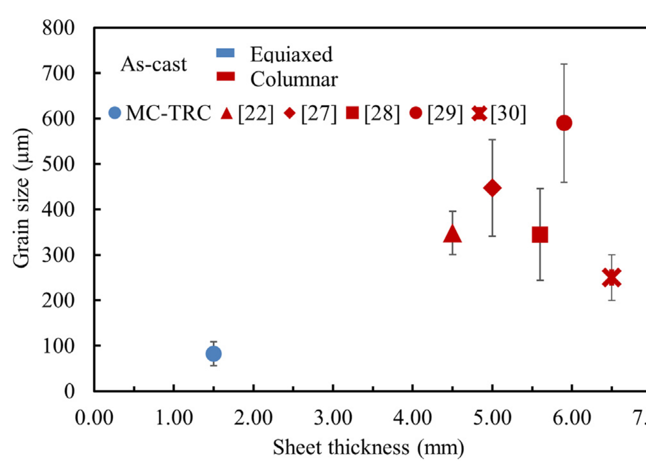

Fig. 6. Comparison of grain size for the as-cast MCTRC AZ31 sheets to that produced by conventional TRC process.

mechanical performance was found to be comparable to those produced by a conventional TRC route plus multi-step downstream heat treatment and hot rolling processing.

The comparison of grain size for the as-cast MCTRC AZ31 alloy sheets to that of conventional TRC sheets is shown in Fig. 6. The grain morphology of the sheets produced by conventional TRC process is mainly columnar structure with a small fraction of equiaxed but coarse grains in the centre of sheet [22,27–30]. On the contrary, the MCTRC sheets possess an equiaxed grain structure over the entire volume of material with an average grain size < 100 μm. It is obvious that it is necessary for the conventional TRC sheets with a coarse columnar structure and severe centre-line segregations to be extensively processed after TRC process to meet the requirement of microstructure and mechanical properties for industrial applications, whereas, on the other hand, the as-cast MCTRC sheets displayed an advantageous microstructure that requires no substantial processing prior to real application.

The final grain size of the AZ31 alloy sheet obtained in the present study after homogenization treatment is compared with those undergone various downstream thermomechanical process for the same alloy is presented in Fig. 7. The average grain size of 15 ± 8 μm was achieved by a fast homogenization at 400 °C for 1 h. To obtain similar grain size and sheet thickness, the as-cast conventional TRC sheet requires multi-passes of hot/cold rolling and related intermediate heat treatment [22,27,28,39].

The tensile properties of the MCTRC AZ31 sheets and those produced by conventional TRC process are presented in Fig. 8, in which the as-cast condition is represented by rectangle symbols and thermal-mechanically processed condition by triangle symbols. The MCTRC sheets show both higher ultimate tensile strength (266.62 ± 10.73 MPa) and ductility (6.02 ± 1.07%) compared with the conventional TRC sheets [22,27,28,39]. The improved performance of the MCTRC sheets is attributed to the grain refinement and uniform chemical distribution due to the employment of the solidification control strategy.

After one hour homogenization treatment at 400 °C, the mechanical properties, especially the ductility of the MCTRC sheets reached 14.53 ± 1.60% on average, which is equivalent to that observed in AZ31 sheets after conventional TRC process and subsequent multi-pass rolling schemes [5,24,27,34,40–43].

The MCTRC AZ31 alloy sheets, with limited homogenization treatment, perform similar to those for the same alloy produced by conventional TRC and extensive downstream processing. This confirms that the solidification controlled MCTRC process is an advantageous approach for producing Mg sheets with high performance at low cost.

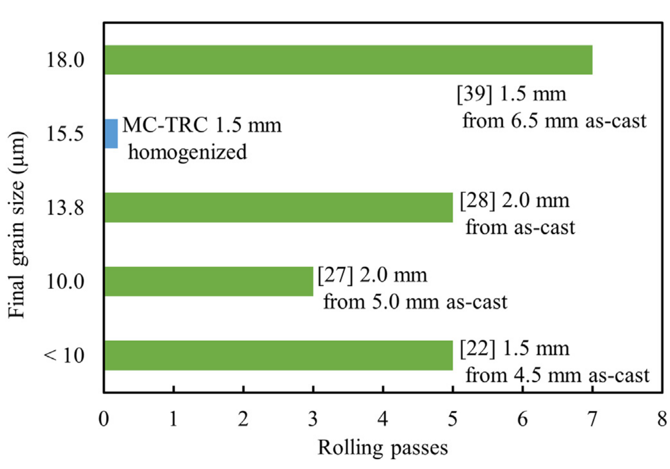

Fig. 7. Grain size obtained for the MCTRC AZ31 sheets in comparison with those for the same alloy produced by conventional TRC with various downstream hot rolling passes.

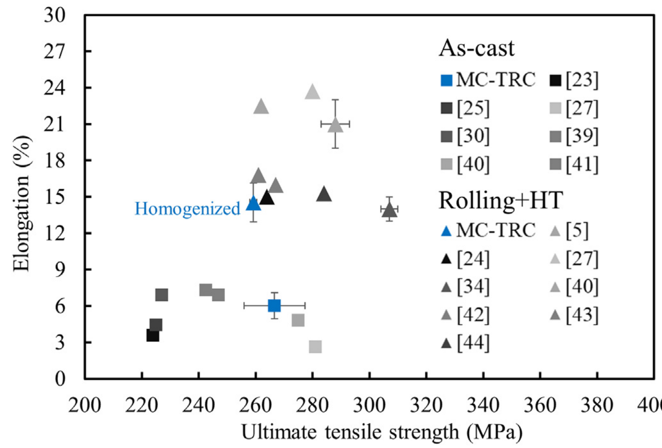

Fig. 8. Mechanical properties of MCTRC AZ31 sheets, in comparison with those by conventional TRC process for the same alloy.

3.3. Isotropic in-planar deformation behaviour

It is generally expected that isotropic mechanical behaviour favour sheet formability and thus improves shape forming performance in multi-axial deformation condition.

The tensile stress-strain curves of homogenized MCTRC AZ31 sheet and the corresponding tensile properties of samples along CD, 45° and TD are presented in Fig. 9(a). Detailed tensile properties are listed in

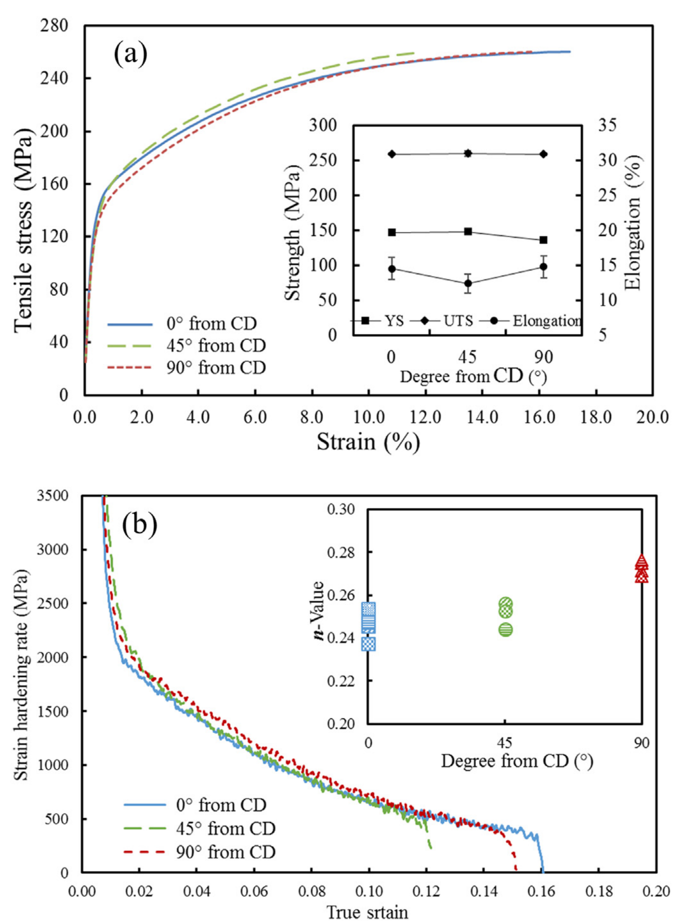

Fig. 9. Tensile deformation response of homogenized MCTRC AZ31 sheet samples: (a) tensile stress-strain curves and mechanical properties and (b) strain hardening behaviour and related strain hardening exponent *n*.

Table 2
The mechanical properties of homogenized AZ31 sheet by MCTRC process in three representative directions.

	Yield strength (MPa)	Ultimate tensile strength (MPa)	Uniform elongation (%)	Elongation to failure (%)
CD	147.2	258.1	12.1	13.4
	146.8	260.5	16.4	17.7
	146.9	259.1	12.3	13.3
45°	145.8	256.4	10.2	11.1
	152.1	263.8	12.2	13.8
	145.8	259.8	11.3	12.3
TD	136.0	260.2	15.3	16.6
	137.1	259.1	13.0	14.1
	135.2	257.2	12.3	13.6

Table 2. Similar stress-strain curves and related mechanical properties have been observed in the stress-strain in three directions. The yield strength in CD and 45° is similar in the range of 145–150 MPa while a lower yield strength of 136.10 MPa was observed along TD, although the ultimate tensile strength was same in all directions with an average value of 259.36 $\pm$ 2.15 MPa. The elongation along CD was 14.7 $\pm$ 2.6% and similarly in TD, being 14.8 $\pm$ 1.6% but a slightly lower elongation of 12.4 $\pm$ 1.4% was obtained in the 45° direction.

The overall strength and ductility in all in-plane directions are substantially similar and such isotropic in-plane tensile behaviour is comparable to that of ZK10 alloy [44] and Mg-1Al-0.1Ca alloy [45] sheets, where the production of these sheets involved either heavy grain refiner addition or dilution of solute that sacrifice strength.

The strain hardening rate and strain hardening exponent n are presented in Fig. 9(b), which shows a uniform and linear hardening behaviour along three in-plane directions. The highest strain hardening exponent was derived to be 0.273 $\pm$ 0.003 along TD. Similar values were derived as 0.246 $\pm$ 0.006 and 0.249 $\pm$ 0.006 for CD and 45°, respectively. For conventional TRC and rolled sheet, the reported strain hardening exponent n is <0.15 [46,47]. Kang et al. [47] suggested that high strain hardening exponent correlates to a large uniform elongation which indicates improved formability. Isotropic in-plane mechanical behaviour of the MCTRC AZ31 sheets suggest promising formability for component stamping at ambient temperature, which could be further advanced at elevated temperature.

The mechanical response to deformation is normally correlated to polycrystalline plasticity [44], presented as the initial texture of sheet materials. In order to understand the isotropic in-plane mechanical behaviour of MCTRC sheet, the crystallographic feature of such sample is analysed.

The texture of homogenized MCTRC AZ31 sheets prior to the mechanical testing is presented in Fig. 10(a). The broad spread of basal pole (over 55°) and significant low intensity of ~3 times of random distinguishes the MCTRC sheets from typical basal intensified Mg sheets produced via conventional TRC process [44,48–50]. The basal texture was due to the rolling deformation of ~15% during MCTRC [51], which was slightly weakened by homogenization. The large spread of the basal peak with a low intensity suggests that a high fraction of basal slip is still available for further deformation along the same route. Likewise, the fact that there are no other orientation peaks suggests that there should be no limits to deformation in any other routes than rolling. The uniform distribution of texture intensity on three representative directions is presented in Fig. 10(b). It can be seen from the figure that the highest basal intensity of ~3 times of random occurs along CD but ~10–20° away from the normal direction. Then a gradual decrease in basal texture intensity takes place with increased tilting angle and diminishes beyond ~55°.

Similar Schmid factor distribution along CD, 45° and TD in Fig. 10 is consistent with the isotropic in-plane mechanical behaviour observed for homogenized MCTRC AZ31 alloy sheet. In Fig. 11(a)–(c), the similar Schmid factor distribution is observed for the basal slip in three in-plane directions. In the soft angle region (>0.4), a plateau of higher fraction (~3.5%) of $\{0002\}\langle 11\bar{2}0\rangle$ is presented. Meanwhile a higher fraction of grains oriented in soft angle for prismatic and pyramid slip systems is presented in CD, 45° and TD directions as shown in Fig. 11(d)–(f) and (g)–(i), respectively. However due to the magnitude higher critical resolved shear stress (CRSS) for these two types of slip system, they will activated much later comparing to Basal slip system. The higher fraction of residue Basal and large amount of prismatic or pyramidal slips in soft region [52] indicate the potential of more deformation can be accommodated in the forming process.

4. Conclusions

The performance of MCTRC process was investigated using an AZ31 magnesium alloy and with the application of novel strategies, in order to produce thin gauge wrought magnesium alloy sheets suitable for direct shape forming without extensive downstream processing. Based on experimental results, following conclusions can be drawn.

(1) A solidification controlled melt conditioned twin roll casting (MCTRC) process has been developed for producing thin gauge magnesium alloy sheets ready for forming with the employment of three novel strategies: intensive melt shear prior to casting; targeting thin gauge sheets and using small scale caster.

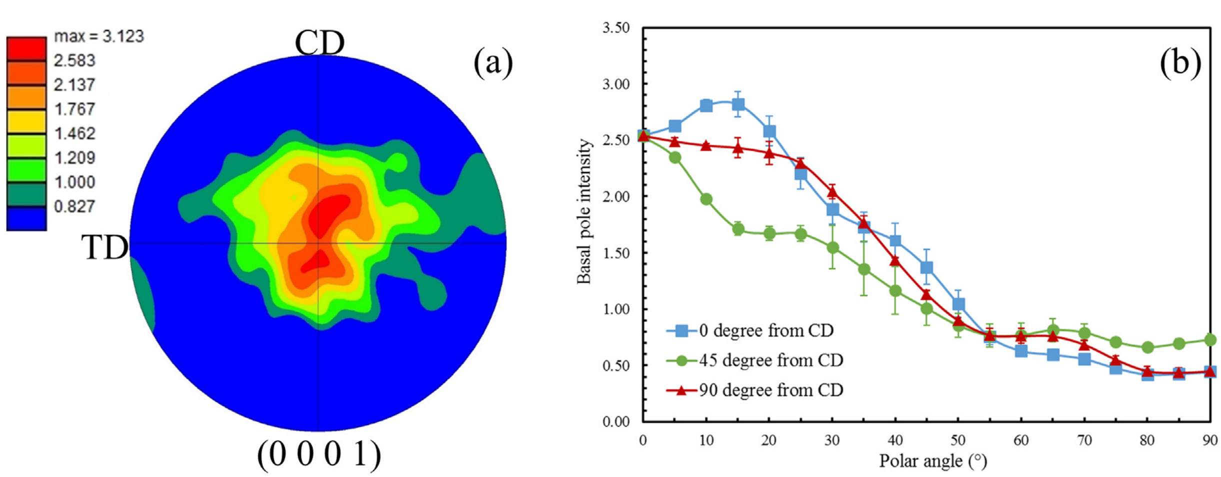

Fig. 10. Recalculated (0001) pole figure (a) and basal pole intensity plot as the function of tilt angle about the sheet normal direction, ND (b), showing a similar spread of texture towards all in-plane directions.

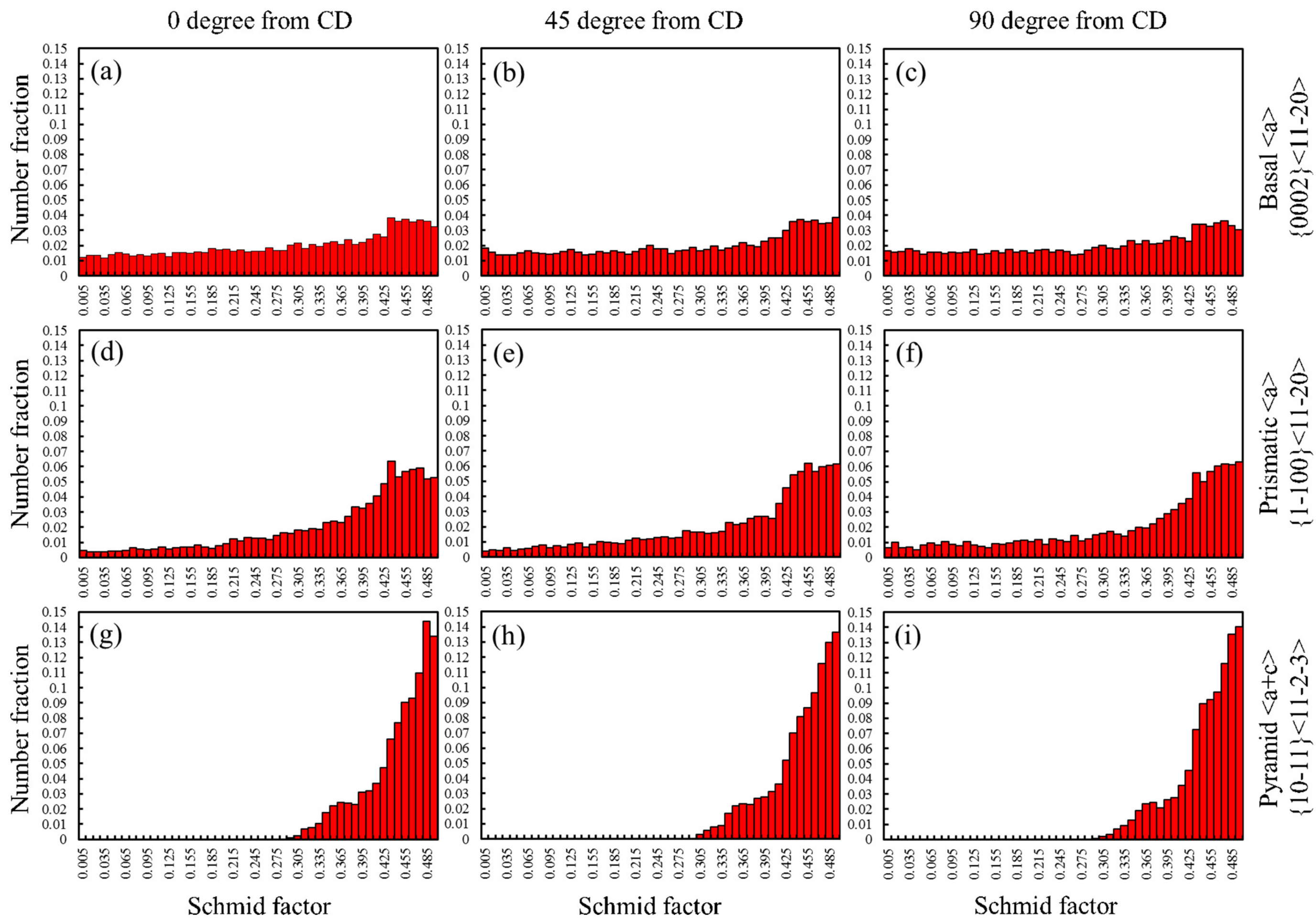

Fig. 11. Schmid factor distribution upon uniaxial tension of homogenized MCTRC sheet in CD, 45° and TD, basal slip system (a–c), prismatic system (d–f), and pyramid system (g–i).

(2) The MCTCR process was successfully tested in the production of AZ31 Mg alloy sheets with a thickness of 1.5 ± 0.1 mm in thickness and 100 ± 10 mm in width. The produced thin gauge AZ31 sheets displayed a uniform, fine and equiaxed grain structure of an average grain size of 83 μm size through sheet thickness and with substantially reduced centre-line segregations.

(3) The texture developed during MCTRC was weak due to improved microstructure and reduced plastic deformation. The homogenized MCTRC AZ31 sheets displayed a good combination of strength (yield strength ~ 150 MPa, ultimate strength ~ 260 MPa) and ductility (uniform elongation ~ 14%), which are comparable to those for the same alloy produced by conventional TRC plus extensive downstream processing including multi-passes hot rolling.

(4) The tensile performance also showed excellent in-plane isotropy with consistent strength, ductility and strain hardening behaviour in three representative in-plane directions, together with weak basal texture and available basal plane in preferred Schmid factor region, indicates a high formability potential for further manufacturing.

CRediT authorship contribution statement

Xinliang Yang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Jayesh B. Patel:** Data curation, Investigation, Methodology, Project administration, Writing - original draft. **Yan Huang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Chamini L. Mendis:** Data curation, Investigation, Methodology, Writing - original draft. **Zhongyun Fan:** Conceptualization, Funding acquisition, Supervision.

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