Final Draft
of the original manuscript:

Huetsch, L.L.; Huetsch, J.; Herzberg, K.; dos Santos, J.F.; Huber, N.:
Increased Room Temperature Formability of Mg AZ31 by High Speed Friction Stir Processing
In: Materials and Design (2013) Elsevier

DOI: 10.1016/j.matdes.2013.08.108
Increased Room Temperature Formability of Mg AZ31 by High Speed Friction Stir Processing

L. L. Hütsch\textsuperscript{a},\textsuperscript{*}, J. Hütsch\textsuperscript{b}, K. Herzberg\textsuperscript{a}, J. F. dos Santos\textsuperscript{a}, N. Huber\textsuperscript{c}

\textsuperscript{a}Helmholz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Solid-State Joining Processes, Geesthacht, Germany
\textsuperscript{b}Helmholz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Experimental Material Mechanics, Geesthacht, Germany
\textsuperscript{c}Helmholz-Zentrum Geesthacht, Institute of Materials Research, Materials Mechanics, Geesthacht, Germany

Abstract

The aim of this work is to investigate the formability at room temperature of the Mg alloy AZ31 by friction stir processing. Defect-free process zones were created using process speeds of up to 10 m/min, the resulting microstructure and grain size were analyzed. Microstructural zones with varying texture were identified by electron backscatter diffraction. Tensile tests supported by digital image correlation analysis revealed different deformation behavior and enhanced ductility in the thermo mechanically affected zone which was associated with the variation in grain size and texture. Finally, the sheet forming behavior of the processed material was investigated, using the Nakajima test method with Hasek specimen geometries. Forming limit diagrams for several process conditions reveal a continuous increase in formability with increasing processing speed. Additionally, the local anisotropy was analyzed by comparison of the R values at the point of highest strain, to quantify the impact of processing on formability.

Keywords: Friction Stir Processing, AZ31B-O, Magnesium alloy, High Speed, Microstructure, Ductility

\textsuperscript{*}corresponding author
Email address: leon.huetsch@hzg.de (L. L. Hütsch)
\textsuperscript{1}Tel.: +49 4152 87 2067

Preprint submitted to Elsevier September 4, 2013
1. Introduction

One of the most urgent challenges in an increasingly industrialized world is the development of more economical and ecological products [1]. The reduction of environmentally harmful pollutants and the increase of fuel efficiency while maintaining structural safety and durability is one of the most demanding topics [2]. In this context, the use of magnesium (Mg) alloys bear the promise to significantly contribute to weight savings [3]. Mg alloys are up to 37% lighter than the widely used aluminium alloys, have excellent strength to weight ratios, are easy to cast [4] and have good recycling capabilities [5].

Their applicability however is often limited by their poor room temperature formability which mostly arises from the high anisotropy inherent to hexagonal close-packed Mg alloys, resulting from a low symmetry of available slip systems. While basal \( \{0001\} <11\bar{2}0> \) is predominant at room temperature, the prism \( a \) and pyramidal \( \alpha \) slip is difficult to activate because of their significantly higher critical resolved shear stresses (CRSS) [6, 7].

A route to increased room temperature formability can be seen in microstructural changes namely grain size reduction and texture modification. A reduction in grain size can be a suitable tool for increased room temperature formability as grain boundary sliding and grain rotation can take place more easily due to a reduction in strain hardening rate [8]. Room temperature formability can also be increased by textural changes, particularly a weakening of the rolling inherent \( (0002) \), high intensity basal texture [9].

Friction Stir Processing (FSP) is based on Friction Stir Welding (FSW) which was developed and patented by TWI, Ltd. in the UK [10, 11]. It has proven to be a suitable process for grain refinement in Mg alloys [12, 13] and has been used to modify the texture [14, 15].

FSP could thus be applied locally on a confined area on material which is to undergo extensive local deformation due to forming processes. The resulting local textural and microstructural changes can be positioned highly localized at regions where increased formability is required.

For this work, FSP was employed to achieve such microstructural modifications. Results show controlled microstructural and textural changes at industrially interesting processing speeds, leading to a significantly increased formability.
2. Experimental details

FSP has been performed on commercially available Mg AZ31 sheet material with a chemical composition of 2.9wt.% Al, 0.74wt.% Zn, 0.29wt.% Mn, and minor impurities of Si, Ni and Cu. The base material was cut into specimen of 2 x 490 x 200 mm. FSP has been carried out in two different modes, as single- and multi line tests. Single line tests were conducted as one pass over the entire sheet length (s. Fig. 1(a)) while multi line tests consisted of multiple passes over the entire sheet length. Each path was displaced by 2 mm into the advancing side (AS) to the prior one and orthogonal to processing direction. The displacement towards the AS has been chosen as the retreating side (RS) offers a less pronounced metallurgical transition area which is thought to be supportive in the current scope. This was repeated ≈ 60 times until a multi line zone of ≈ 120 mm in width was created (s. Fig. 1(b)). Before each repeated processing step, the tool and sheet has been cooled to room temperature using compressed air.

![Figure 1: (a) Single line specimen. (b) Multi line specimen.](image)

FSP has been carried out using a Tricept T805 five axis parallel kinematic robot in force control mode incorporating an independent force control unit acting as a sixth axis.

2.1. Tool

The tool as shown in Fig. 2(a) was manufactured from high performance Cr-Mo-V steel [16] with a φ13 mm scrolled shoulder as well as a threaded triflat probe set to a length of 1.8 mm having a tapered diameter from φ4 mm close to the shoulder to φ2.5 mm at the tip. This geometry was
chosen as previous studies conducted on AZ31 by Padmanaban et al. [17] revealed a local minimum in grain size (GS) when utilizing shoulder to probe ratios of $\approx 3$.

![FSP tool used in this study. (b) FSP tool with coordinate system and tilt angles.](image)

Figure 2: (a) FSP tool used in this study. (b) FSP tool with coordinate system and tilt angles.

2.2. Process Parameters

The process parameters were developed with the primary aim of introducing as little heat into the base material as possible in order to minimize grain growth and static recrystallization (SRX). For a better understanding of the utilized processing parameters, the coordinate system and tilt angles are detailed in Fig. 2(b) in which x represents the processing direction. Defect free process zones were achieved using the processing speeds (PS) listed in Tab. 1. All remaining parameters namely axial force, rotational speed (RPM) and tilt angles ($\varphi_y$ and $\varphi_x$) were systematically adjusted until defect free process zones were obtained [18].

<table>
<thead>
<tr>
<th>Condition</th>
<th>PS [m/min]</th>
<th>Axial force [kN]</th>
<th>RPM [1/min]</th>
<th>PS/RPM [(mm/s)/(rot/min)]</th>
<th>$\varphi_x$ [$^\circ$]</th>
<th>$\varphi_y$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>8</td>
<td>2000</td>
<td>0.008</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>14</td>
<td>2250</td>
<td>0.022</td>
<td>0.5</td>
<td>-1</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>15</td>
<td>2500</td>
<td>0.033</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>D</td>
<td>7</td>
<td>15</td>
<td>3250</td>
<td>0.036</td>
<td>1.5</td>
<td>-1</td>
</tr>
<tr>
<td>E</td>
<td>10</td>
<td>20</td>
<td>3500</td>
<td>0.048</td>
<td>1.5</td>
<td>-1</td>
</tr>
</tbody>
</table>
2.3. Microscopy

Optical microscopy (OM) analysis using a Leica DM IRM has been applied as an initial approach to rule out continuous process zone (PZ) discontinuities. It should be pointed out that OM of cross sections will only give local insight into the PZ and that imaging techniques such as X-Ray investigations would need to be applied in order to rule out PZ discontinuities over the entire sample length. Electron backscatter diffraction (EBSD) investigations were conducted on a dual beam FEI Nova Nanolab 200 scanning electron microscope equipped with a field emission gun. An EDAX TSL PEGASUS system equipped with a Hikari camera was used with acceleration voltages in the range between 15 kV and 20 kV, a working distance of 10 mm and a current of 2.2 nA. Orientation mapping using automatic beam scanning was carried out with a step size of 0.5 - 2 \( \mu \)m. The obtained results were analyzed using the TSL OIM Analysis V5 software. The average confident index for all investigated samples was within the order of \( \approx 0.8 \) as comparison measurements performed by EDAX Inc. [19] on fcc material showed a 95\% probability of correctly indexed patterns at confident index > 0.1. Grains comprising of \( \leq \) three pixels were removed from the scanned maps using the inherent grain-dilatation method of the TSL software to ensure the highest reliability of the obtained microstructural pictures. Perturbing boundaries which are often caused by orientation noise were removed by a 2\(^{\circ}\) lower limit boundary disorientation cut off. Low angle boundaries were separated from high angle boundaries by using the 15\(^{\circ}\) criterion. Grain size measurements were performed using the software inherent line intercept method.

It should be noted that samples for EBSD analysis were specially processed to rule out SRX. This has been done by submerging the entire setup including, test specimen, backing bar and all clamping equipment in a container filled with liquid nitrogen until the equipment was cooled down to \( \approx -196 \) \(^{\circ}\)C. FSP was conducted directly after removing the equipment from the container. In this way, the thermal trail of the tool was reduced to the region directly below the shoulder. As SRX occurs at temperatures around 205 \(^{\circ}\)C [20], most of the involving effects, including grain growth can be avoided.

All microscopy samples were prepared by cutting processed material orthogonal to processing direction. For primary grinding, SiC paper of grit sizes between 1200 to 4000 was used. The samples were then finalized by polishing with Struers OPS solution and electro polishing.
2.4. Tensile Tests

Tensile tests have been carried out in accordance to the DIN EN 10 0002 standard at a constant traverse speed of 0.7 mm/s on a Zwick/Roell BZ1 tensile machine incorporating a 100 kN load cell equipped with a MTS 634.25F-24 strain gauge ($l_0 = 50$ mm). Tensile samples were extracted orthogonal to processing direction and left in the as processed condition. Local strain evolution was evaluated using a digital image correlation (DIC) system and an exemplary image of a sample with overlaid strain is shown in Fig. 3(a). Additional information on the system and its functionality can be found elsewhere [21].

![Figure 3: (a) Tensile sample with overlaid strain field. (b) Hasek sample with overlaid strain field. In the center a point is indicated at where anisotropy investigations were carried out.](image)

2.5. Forming Limit Tests

The influence of FSP on formability has been evaluated for the base material as well as for condition C and E (Tab. 1) in accordance with the sheet metal forming standard ISO 12004 [22, 23] using sample geometries introduced by Hasek [24–27] and concurrent to the Nakajima [28] test method. Due to geometric constraints, the geometry of the Hasek samples was scaled by 1/2 resulting in
100 mm with respectively scaled cutouts as listed in Tab. 2. An exemplary Hasek sample with overlaid strain field can be seen in Fig. 3(b). For each geometry, five samples were cut from multi-line processed base material in such a way that the cutouts point into processing direction and machined to a thickness of 1 mm from top and bottom. Tests were conducted on an Erichsen hydraulically driven testing machine with a stainless steel punch with a Ø100 mm dome. Machine parameters were set to 200 kN clamping force and 60 mm/min punch speed. The tribological system, which is necessary to minimize friction between sample and punch, was investigated on dummy samples. Best results have been achieved using oil in combination with poly-ethylene foil of 0.05 mm thickness and Ø33 mm. All tests were conducted until fracture, meanwhile the local strain evolution has been measured in situ using a DIC system.

### 3. Results and Discussion

#### 3.1. Process parameters and consolidation mechanisms

In order to put the process parameters into perspective, a comparison with published work conducted on FSW and FSP of Mg AZ31 [29–31] is presented in Fig. 3.1. Herein the PS/RPM ratio, also called the weld pitch [32, 33], can be considered as a preliminary value for the energy input introduced by the process. Most of the recent studies have been conducted at PS < 1 m/min using moderate RPM of \( \approx 1000 \text{ rpm} \) which results in PS/RPM ratios ranging from 0.001 to 0.02 \([\text{mm/s}]/[\text{rot/min}]\). In the present study this ratio ranges from 0.008 \([\text{mm/s}]/[\text{rot/min}]\) in condition A to 0.074 \([\text{mm/s}]/[\text{rot/min}]\) in condition E. Such high weld pitches result in continuously decreasing temperatures in the PZ [18] which in turn results in a decreased shear layer size. As previously investigated in a slip/stick comparison [34], slip models yield better results at higher temperatures while stick models are to be used at lower temperatures. Keeping this in mind, a full stick condition has been used to calculate the travel of the tool before the center of the probe performs one full rotation. At the outer circumference of the probe, using a diameter of \( \approx 4 \text{ mm} \), the material will thus

<table>
<thead>
<tr>
<th>Geometry</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutout radius [mm]</td>
<td>40</td>
<td>36.25</td>
<td>32.5</td>
<td>28.75</td>
<td>25</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Hasek sample geometry.
Figure 4: Log weld pitch over log processing speed.

have to travel over 12 mm around the probe while being translated over 2.8 mm into the processing direction. Due to the additional translational movement, the consolidation mechanism in high speed FSP could in principle be divided into a stirring and an extrusion component. This distinction is especially important with regard to the recrystallization behavior and texture development. In the extrusion of Mg, the level of dynamic recovery is sufficiently low to allow dynamic recrystallization (DRX) above a temperature of 240°C. Thus, after deformation, fine grains are formed at original grain boundaries, leading to material strengthening due to the substructures formed during DRX. AZ31 in particular, work-hardens in the range between 180 - 240°C by deformation mechanisms induced by twinning as described by Friedrich et al. [35]. It can therefore be argued that the two deformation processes, stirring and extrusion, are contributing to the formation of the process zone. The thermal input is mainly governed by the stirring component whereas plastic deformation stems from stirring as well as extrusion.
3.2. EBSD

In depth EBSD investigations have been conducted to identify metallurgical zones of reduced grain size and textural changes potentially affecting the deformation behavior. Multiple scans were positioned next to each other stretching over the entire process zone. As condition E (see Tab. 1) represents the upper end of FSP parameters with respect to grain size reduction by minimizing the thermal input into the system, it has been chosen for EBSD analysis.

The grain size and intensity distribution from the heat affected zone (HAZ) to the thermo mechanically affected zone (TMAZ) and stir zone (SZ) is displayed in Fig. 5. While the grain size continuously decreases towards the SZ, the intensity exhibits a sharp increase from the TMAZ to the SZ. The reduction in grain size can be attributed to the severe plastic deformation and input of frictional heat during FSP leading to recrystallization [36]. The limited grain growth can be attributed to the high PS resulting in a small thermal trail following the passing tool which gives the material limited time for grain growth [18]. The increase in textural intensity on the other hand can be attributed to the reorientation of the basal planes towards the processing direction [37].

As the observed reduction in grain size paired with a low texture intensity is desirable for enhanced deformability, the transition zone between the TMAZ and the beginning of the SZ can thus be considered as regions of interest. The corresponding pole figures and inverse pole figure maps of the base material and TMAZ are shown in Fig. 6.

3.2.1. EBSD - Base Material

As depicted in Fig. 6(a) the base material exhibits the expected rolling texture with the (0002) basal planes parallel to process direction and a grain size between 3.8 \( \mu \text{m} \) and 3.6 \( \mu \text{m} \). While the intensity ranges between 6.8 and 5.2 the high angle boundary (HAB) to low angle boundary (LAB) ratio is 7.8 (88.6 % to 11.4 %) with LABs primarily aggregated within larger grains. The overall misorientation distribution is depicted in Fig. 7. It features a small peak at between 5° and 10°, large peak between 85° and 90° and an accumulation around 30°. While the small peak at between 5° and 10° is not associated with a particular axis and can thus be related to the LAB, the large peak between 85° and 90° shows a preference for a \(<1\overline{2}10>\) rotation axis and can therefore be attributed to a high amounts of \{10\overline{1}2\} twinning [38]. The accumulation around 30° suggests a high amount of HAB within the base material.
3.2.2. EBSD - TMAZ

The PF and IPFM of the TMAZ are shown in Fig. 6(b). The (0002) basal planes are shifted towards the processing direction and concentrated at \( \approx 30^\circ \) with a slight shift out of the normal direction (ND). The (10\(\bar{1}\)0) face planes are consolidated and are almost evenly distributed within a thin band. Similar results on Mg have been obtained using equal-channel angular pressing and equal channel angular extrusion which enhanced low temperature superplasticity [39, 40]. These results show an alignment of (0002) basal planes with the theoretical shear plane leading to higher elongation to failure, if dislocation slip is the dominant rate controlling mechanism.

While the grain size in the TMAZ is significantly reduced to a range between 2.2 \( \mu \)m and 1.6 \( \mu \)m, the intensity is in a transition region between 4.9 and 9.8. The misorientation distribution in the TMAZ shows no prominent peak compared to the base material but a higher accumulation around 30\(^\circ\) and is weak towards 0\(^\circ\) and 90\(^\circ\). Interestingly the TMAZ - HAB to LAB ratio of 4.7 (82.6 \% to 17.4 \%) is comparable to the base material ratio. The reduction in grain size as well a the dominant formation of HAB indicates an enhanced deformation ability by a reduction in flow stress.
Figure 6: Pole figures (PF) and the corresponding inverse pole figure maps (IPFM) of the base material (a) and TMAZ (b).

as previously investigated on micro tensile samples [41, 42].

The higher peak around 30° in Fig. 7 can be attributed to the higher impact of DRX involving an increase in grain boundary misorientation and the transition of LAB to HAB as previously described for tensile tests at elevated temperatures [43].

The above suggests that despite aggressive cooling from the surrounding, the material underwent DRX and was able to form low aspect ratio grains with a vast majority in the HAB domain. Additionally, almost no twins of any kind were present within the TMAZ. These results suggest the TMAZ to be a zone of potentially higher deformability.
3.3. Tensile Testing

In order to investigate whether the EBSD results are indeed transferable to non-cooled samples, single line tensile tests with in situ DIC analysis were conducted. The tensile test results are listed in Tab. 3.

An example of the local strain evolution as captured by the DIC system is depicted in Fig. 8. The local strain is overlaid onto the tensile sample while the progress is marked in each image by a time stamp. Up to step I, the entire sample deforms elastically throughout all regions. This behavior continues up to step II, at which point first local strain concentrations are emerging at the TMAZ of the AS and RS. In the course of the test (step VI to VII) the strain field on the RS intensifies (b) until in step XI an additional strain field emerges at the RS (c) which will finally lead to fracture in step XIII (d). The base material strain evolution continuously increases up to step XII. As this strain is no longer evident after fracture, it can be concluded that a large fraction of the base
material deforms in a purely elastic manner.

Conclusively it can be said, that the global deformation during tensile testing is located at the borders of the process zone being the juncture between TMAZ and HAZ and almost no plastic deformation seems to be present in the base material; effectively shifting the entire strain to the process zone. As the samples have been tested in the as processed condition, the possibility of strain localizations due to notch effects need to be considered. This has been done by comparing specimen of different processing conditions which having various degrees of surface roughnesses. The results show, that independent of surface condition a strain localization takes place at the previously described TMAZ - HAZ interface. A more detailed analysis and comparison of the local strain evolution to other process parameters can be found in the literature [41].

To further investigate the observed phenomena, it was decided to create multi line specimen by expanding the TMAZ to a larger area.

### 3.4. Forming limit diagrams

Formability tests were conducted on multi line samples in condition E and C. By using the data gathered from the DIC system, forming limit diagrams (FLD) have been generated. The FLD results
have subsequently been used to construct forming limit curves (FLC) as presented in Fig. 9. Each point within the FLCs is built up out of five samples of one geometry, the lines between the points are interpolations. For a more coherent representation the boundaries for stretch forming $\varphi_1 = \varphi_2$ as well as uniaxial tension $\varphi_1 = -2 \cdot \varphi_2$ are included. Every strain below the respective FLC can be considered a region of safe deformation. Strains higher than the respective FLC will eventually lead to fracture. It should be noted that the interpolations between the points do not necessarily represent the lowest possible strain and localized necking might occur before the respective FLC is reached but as this holds true for all tested sample, a comparison with the tested FLC regime is still valid. The overall shift of all FLCs towards positive minor strains can be ascribed to the combination of the flat sheet and the small radius punch resulting in limited amount of stretch forming at the beginning of the test.

Overall, the processed material exhibits a continuous increase in formability with increasing PS. A detailed comparison of the processed material over the base material is presented in Fig. 10. Within the uniaxial tensile and plane strain regime (sample geometry I and II), an increase of almost 30 % for condition C and over 60 % for condition E could be reached. Between the plane strain and stretch forming regime (sample geometry III to VI) increases of up to 50 % for condition E and over 100 % for condition E can be achieved. Close to the stretch forming regime (sample geometry VII) the two conditions are very similar with a formability increase of over 30 %. The observed increases can be attributed to the (0002) basal plane shift, as previously reported using repeated unidirectional bending on AZ31 to obtain textural changes [44].
3.5. Anisotropy

In order to investigate the effect of FSP on the materials anisotropy the plastic strain ratio R has been evaluated using a DIC system. Due to magnesiums inherent basal texture, the deformation is usually inhomogeneous in nature which in turn has a large influence on the mechanical properties. The R-value can thus give an insight into the different anisotropic responses between processed and base material and has been calculated over the entire surface of the samples for every stage using an adapted R value equation as presented in Eq. 1 in which $\epsilon_x$ and $\epsilon_y$ are the strains in x and y respectively.

$$ R = \ln \left( \frac{1 + \epsilon_x}{1} \right) / \ln \left( \frac{1}{((1 + \epsilon_y) \cdot (1 + \epsilon_x))} \right) $$

It should be noted that due to the $\ln$ in the denominator of this equation, most of the results have a negative sign. Previous investigations by Kang et al. [45] have shown that Mg alloys show a high sensitive to the measurement method of the width and thickness strain. The authors argue, that due to the nonlinear evolution of the strain distribution on the sheet surface, strains should be
Figure 10: Increase in major strain for condition C and E over the base material.

measured at certain points rather than over the entire sample length. Having the R value calculated over the entire sample, the center point of each sample (s. Fig. 3(b)) has thus been chosen for detailed analysis as deformation is mainly localized in this area.

In Fig. 11 the resulting R values are plotted starting from 60 % into the test (initial stages showed increased levels of noise) until the last frame before fracture for the base material, as well as for conditions C and E for the geometries I, IV and VII. The overall trend shows an increasingly homogenized anisotropy behavior within the different processing conditions as the strain condition moves from uniaxial tensile (geometry I) to stretch forming (geometry VII).

The largest differences in R value compared to the base material can be noticed for geometry I. While after 60 % of the test the processed and the base material samples exhibit comparable R values, a consequent increase towards the end of the tests is evident, indicating better drawing capabilities in the uniaxial tensile regime for the processed material. The observed increase is partly reduced for samples of geometry IV, as only slight differences in R value can be noticed towards
the end of the tests. It can thus be argued that the transition regime of uniaxial steady tension and deep drawing is becoming less affected by the previously described texture and microstructural modifications. This trend continues as almost no difference in anisotropic behavior can be seen for samples of geometry VII.

While the effect of increased formability can mainly be attributed to the (0002) basal plane shift, the understanding of the changes in R value developments must include the consideration of the microstructural changes. As previously investigated, increasing global strain leads to an increased R value [46] which is most pronounced in the tension regime of ultra fine grained (<3μm) samples, resulting in ductility improvements [47]. The authors argue, that the higher R value yields a higher amount of non-basal <a> slip near grain boundaries in the tensile regime which confirms the observations of this study.

The forming limit tests confirm the initial hypotheses that grain refinement combined with controlled texture modification via FSP is a suitable tool to generate enhanced room temperature ductility in Mg AZ31.
4. Conclusions

From the presented research, the following conclusions can be drawn:

1. High speed Friction Stir Processing was successfully performed on Mg AZ31 sheet material at processing speeds between 1 and 10 m/min in single and multi line configurations.

2. EBSD analysis of the process zone revealed the TMAZ to be prone for enhanced deformability as it features recrystallized, low aspect ratio grains, showing a great mount of high angle boundaries. Additionally, the grain size was significantly reduced to values below 2 \( \mu \text{m} \) resulting in an ultra fine-grained microstructure; furthermore the (0002) basal planes of the base material were shifted towards the processing direction.

3. Tensile testing supported by DIC analysis confirmed the TMAZ to be most prone to enhanced deformation as the samples underwent the highest amount of local deformation in this region.

4. Formability tests conducted on multi line samples revealed a continuous increase in deformability with increasing processing speed, resulting in an increase of over 100 % compared to the base material in some strain conditions. This increase can be attributed to the shift in (0002) basal planes towards a more favorable deformation direction and a reduction of the critical resolved shear stresses.

5. Local anisotropy analysis revealed an increased R value in the tensile regime of the forming limit diagram for the processed material compared to the base material. Grain refinement accompanied by the high amount of high angle boundaries can be identified as the responsible mechanism for this phenomenon.
List of Tables

1  FSP parameters used in this study. .................................................. 4
2  Hasek sample geometry. ................................................................. 7
3  Tensile results for BM and processed material in all processing conditions and direc-
tions. ............................................................................................... 13

List of Figures

1  (a) Single line specimen. (b) Multi line specimen. ............................... 3
2  (a) FSP tool used in this study. (b) FSP tool with coordinate system and tilt angles. 4
3  (a) Tensile sample with overlaid strain field. (b) Hasek sample with overlaid strain field. In the center a point is indicated at where anisotropy investigations were carried out. ................................................................. 6
4  Log weld pitch over log processing speed. .......................................... 8
5  Grain size and intensity distribution over the process zone in condition E. . . . . 10
6  Pole figures (PF) and the corresponding inverse pole figure maps (IPFM) of the base material (a) and TMAZ (b). .......................................................... 11
7  Low angle and high angle boundary distribution of the base material and TMAZ as depicted in Fig. 6. ................................................................. 12
8  Image series of local strain evolution during tensile testing of a sample processed in condition E. The evolution of strain is colour coded and the progress are indicated by time steps below each image. ......................................................... 14
9  Resulting FLC for the base material as well as condition C and E. ............ 15
10 Increase in major strain for condition C and E over the base material. .......... 16
11 Anisotropy over test progress in the base material as well as condition C and E for geometry I, IV and VII. ............................................................ 17
References


