Aluminum is the most abundant metal occurring in the earth’s crust and is the second most commonly used material after steel. The aluminum production is also the most energy-intensive one and requires almost 200 gigajoules per ton, which is tenfold compared to steel production [1]. Therefore, the secondary metallurgical route is recommendable as it requires only 7% of the energy of the primary route [2]. However, the secondary metallurgical route has, with respect to aluminum chips, a material loss of 20 to 25%, since the surface to volume ratio has a too high characteristic value [1]. The direct recycling of aluminum chips by extrusion to final products was first mentioned and patented by Stern in 1945 [3]. Following investigations by Güley et al. [4] and Haase et al. [5] have already been able to achieve an approximation of the mechanical properties of the reference cast materials by varying die geometry, extrusion temperature and extrusion ratio. As known from previous research, the application of integrated extrusion and equal channel angular pressing (iECAP) leads to a finer microstructure and increased hardness [5]. An in-depth analysis of the arising defects during extrusion and their influence on the hardness distribution while using aluminum alloy EN AW-6060 is investigated in this research work.

### Material

The chemical composition of aluminum alloy EN AW-6060 is given in Table 1. Prior to experiments, chips were pre-compacted using a hydraulic press with a diameter of D = 60 mm and a compacting force of F = 500 kN without using a lubricant. In relation to casting material (ρ = 2.7 kg × dm⁻³),

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Mg</th>
<th>Cu</th>
<th>Mn</th>
<th>Fe</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Others</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.45</td>
<td>0.372</td>
<td>0.016</td>
<td>&lt;0.05</td>
<td>0.208</td>
<td>0.001</td>
<td>0.005</td>
<td>0.014</td>
<td>0.005</td>
<td>bal.</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of EN AW-6060 blocks (wt.-%) [6]
the chip-based blocks reach a density of 78%. For the pre-compacting process of the chip blocks, a constant mass of m = 550 g was used [6].

| Test methodology |

EN AW-6060 profiles were manufactured by using a Collin 2.5 MN extrusion press and a constant recipient temperature of T = 450 °C. To avoid too high shear stresses in the contact zone between material and recipient, the ram speed was constant with v = 1 mm s⁻¹. Two different profiles were extruded: a round and a square profile. The diameter of the round flat-face die (RF) was D_RF = 20 mm and the square flat-face die (SF) had a width of W_SF = 20 × 20 mm².

Therefore, the extrusion ratio (ER) of the specimen corresponds to ER_RF = 10.0 and ER_SF = 8.6. Before the extrusion process, the billets were pre-heated for 6 hours at a constant temperature of T = 550 °C. Next to extrusion, the profiles were cooled down in air to room temperature without additional heat treatment.

Similar to Siddique et al. [8], micro-computed tomography analyses (CT scans) were used to determine the quantity and distribution of internal defects (RF_CT and SF_CT). For the scans, a Nikon XT H 160 system was used with an operating voltage from 30 to 160 kV and a beam current from 0 to 0.5 mA. To avoid the detection of inexist-ent micro defects, which can appear because of a too low contrast difference, a Gauss filter fitted the contrasts of the CT scans. This filter is intended to blur an image without losing edges or important structures. The cross sections of the samples were not analyzed, since they are caused by manually induced errors during sample preparation. The specimens were divided into three different zones, depending on their position in the extruded sample: profile, transition and contact zone.

An EMCO-TEST DuraScan 70 G5 hardness testing system was used to determine Vickers hardness distribution of the ground and polished surfaces of RF and SF specimens. The applied loading force was held for 10 s at room temperature. The hardness measurements with HV0.1 indents were carried out fully automatically on a pre-defined grid on the surface with a distance of about 440 μm between the indents. Only specimens of the profile zone were tested, because they are the only industrially usable parts. For each of both geometries, hardness mappings were performed on two samples (RFHV and SFHV).

Figure 1 shows the indents of the hardness mapping of a SF specimen. RF specimens were analyzed analogously to the illustrated SF specimen.

## Results

Computed tomography analysis. The CT analysis of the profile zone of RF specimens has not detected any defects (see Figure 2a). Only surface defects are visible, which do not represent internal structural defects and are caused by the friction between material and recipient. Defects in the cutting surface of the specimens were also not analyzed, because they were induced manually by cutting during specimen preparation.

In the transition zone between the profile and contact zone, the number of defects increases significantly (see Figure 2b). A clear difference between the almost defect-free inner region and the outer region is obvious. The defect amount reaches its maximum in the block contact zone (see Figure 2c). Large defects are clearly visible in the edge area as well as potentially entrapped air pores.

Profile samples of SF_CT specimens have an increased defect quantity, particularly in the corners (see Figure 3a). It can be assumed, that this is caused by an increased shear stress in the outer edge and a lower one in the inner region, which can lead to an incomplete welding of the chips and renewed fractures in the direct contact area [4, 6]. In the contact zone, the defect quantity increases analogous to the RF_CT specimens (see Figure 3b). The maximum number is again reached in the contact zone. However, in some cases, a small surface delamination can be observed (see Figure 3c).

The steady increase of defect quantity in the direction of the block transition, which was observed for both specimen types, is occasionally attributable to the entrapped air during extrusion and welding of the blocks. This results in a volume increase, which can lead to surface bulging or delamination of the specimens in the transition section.
Both, RF\textsubscript{CT} and SF\textsubscript{CT} specimens, show a clear difference between the inner and outer edge region. Most defects are located in the transition regions between these two areas in both specimen types. The outer region is exposed to a higher temperature due to the shear stress and the friction between material and recipient, so that a dynamic recovery during and static recrystallization after the extrusion occurs.

In order to validate the assumption that the profile zones of RF\textsubscript{CT} and SF\textsubscript{CT} specimens have a consistent lower defect quantity, the volume of three profiles were analyzed for each specimen type. The minimal defect size corresponds to the resolution (Res) of the CT scan with a mean value of about Res\textsubscript{RF} = 23.26 μm and Res\textsubscript{SF} = 28.95 μm.

As can be seen in Table 2, the scans confirm a very low defect quantity throughout the entire volume of the profiles. No defects could be detected during the analysis of RF\textsubscript{CT} specimens. The defect quantity of SF\textsubscript{CT} specimens decreases exponentially with an increasing defect volume, as shown in Figure 4. An in-depth analysis of the transition and contact zones has not been carried out, since these zones are not further investigated due to their high defect quantity.

**Hardness distribution.** During extrusion of EN AW-6060, a dynamic recovery occurs preferentially comparable to dynamic recrystallization due to increased stacking fault energy, which leads to dislocation movement and annihilation of crystallographic defects. During the extrusion process no dynamic recrystallization takes place because of the chemical composition, only afterwards, when the material leaves the die, static recrystallization occurs [6]. Since the dynamic recovery predominates in the edge region, its hardness distribution has a slight positive deviation compared to the central region. Microscopic investigations revealed a peripheral coarse grain (PCG) in the edge regions of specimens (see Figure 5). The size of the PCG depends on the rod temperature [6] and therefore, it is very clearly recognizable at a temperature of T = 550 °C in the edge region. It can be assumed that the temperature in the edge region deviates upwards in comparison to the inner structure, due to the friction between material and recipient.

Furthermore, the hardness is influenced by the welding between the aluminum chips. Based on Donati and Tomesain [7], Güley et al. [4] defined a critical shear stress for breaking the oxide layer of the chips. If the oxide layer is broken, conventional weld formation will occur [7].

As can be seen in Figure 6a, RF\textsubscript{HV} specimens have a very constant hardness distribution with an average value of 47.7 HV0.1 (see Table 3). Slight deviations in the edge

![Figure 4: Defect quantities and defect volumes of SF\textsubscript{CT} profile specimens; the volume is represented as the summed defect volume of volume intervals, in order to provide a better overview; the quantity of large defects decreases exponentially, while a higher quantity of small defects exists](image)

### Table 2: Defect validation of RF\textsubscript{CT} and SF\textsubscript{CT} profile specimens

<table>
<thead>
<tr>
<th></th>
<th>RF\textsubscript{CT,1}</th>
<th>SF\textsubscript{CT,1}</th>
<th>SF\textsubscript{CT,2}</th>
<th>SF\textsubscript{CT,3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect percentage (%)</td>
<td>0</td>
<td>0.03</td>
<td>0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>Defect quantity</td>
<td>0</td>
<td>196</td>
<td>395</td>
<td>32</td>
</tr>
<tr>
<td>Minimal volume (μm³)</td>
<td>-</td>
<td>24,374</td>
<td>24,373</td>
<td>24,036</td>
</tr>
<tr>
<td>Maximal volume (mm³)</td>
<td>-</td>
<td>2.30</td>
<td>7.77</td>
<td>4.11</td>
</tr>
</tbody>
</table>

![Figure 5: Peripheral coarse grain edge (PCG) in the cross section of an RF specimen](image)

![Figure 6: a) Hardness distribution with a concentric decrease to the center, b) 3D illustration; RF\textsubscript{HV} profile specimen; the x- and y-axes show the coordinates of the indentation grid](image)
areas occur, caused by a higher shear stress and temperature during the extrusion. SFHV specimens show a more inhomogeneous hardness distribution (see Figure 7a). The average hardness value is 42.9 HV0.1. It is obvious, that the center region shows a negative deviation compared to the edge region. This could indicate that the sufficient stress has not occurred in the center and therefore the chip welding process proceeded insufficiently, since the oxide layers broke not in total. The lower stress is based on the lower extrusion ratio $E_{RS} = 8.6$.

### Conclusion and outlook

In addition to the energy-intensive secondary metallurgical recycling route, direct extrusion of aluminum chips provides an alternative production process of final profiles. Mechanical properties have a direct dependency on the welding quality of the extruded pre-compacted chips. Micro-computed tomographic defect analysis as well as macro-hardness mappings allow efficiency assessment of two geometrically different dies.

The partial subdivision of extruded EN AW-6060 chip specimens into three different zones yields detailed results in the computed tomographic defect analysis. Explicitly the profile zones of round (RF) and square (SF) flat-face die specimens show a very low defect quantity with small volume. However, the rectangular geometric shape leads to an increased defect volume being visible in the corners of SF specimens due to low shear stress. The transition and contact zone show the highest defect quantity, explicitly in the cross transition section between the fine-grained inner region and the peripheral coarse grain. Increasing defect quantity is due to air inclusions produced during extrusion and welding of the blocks. These inclusions can lead to a volume increase, which can lead to a surface bulging and delamination of specimens.

Hardness mappings for RF specimens also show better results in contrast to SF specimens. The inward concentric decrease in hardness values has a smaller range than the linear drop of SF specimens. Therefore, the hardness is distributed more homogeneously. The increased hardness in the outer region of SF specimens is caused by the peripheral coarse grain induced by a higher shear stress than in the middle region and the dynamic recovery which is affected by a higher temperature provoked by friction between material and recipient.

For further reduction of defects and hardness increase, the use of a higher extrusion ratio offers certain potential. As shown in the comparison of RF and SF specimens, RF specimens have a higher hardness due to a higher extrusion ratio. Furthermore, it is possible to reduce the number of defects, since it comes to a higher shear stress, friction and friction-induced temperature increase. The use of a more complex die is also very promising. Within the investigation of mechanical properties of extruded profile specimens with more complex die geometries, the specimen preparation varies with respect to the heat treatment plus storage duration and the complexity of die geometry. Based on the specific mechanical properties, a qualitative and quantitative description of the process-structure-property-relationships will be determined.

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![Figure 7: a) Hardness distribution with a linear decrease to the center, b) 3D illustration; SFHV profile specimen; the x- and y-axes show the coordinates of the indentation grid](image)
Abstract


Bibliography

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The authors of this contribution

Philipp Goerlich, MSc RWTH Aachen University, born in 1989, studied Industrial Engineering with specialization in Materials and Process Engineering at RWTH Aachen University, Germany. After his master thesis, he has been working in the Department of Materials Test Engineering (WPT) at TU Dortmund University, since 2016. His research focus is on the determination and expansion of the application limits in the metal forming recycling of aluminum chips.

MSc Ronja Scholz, born in 1987, studied Sales Engineering and Product Management with specialization in Materials Engineering at Ruhr University Bochum, Germany. After her master thesis, she has been working as a scientific assistant in the Department of Materials Test Engineering (WPT) at TU Dortmund University, Germany, since 2014. Her research focus is on fatigue and fracture of resource-efficient composite materials. Prof. Dr.-Ing. Frank Walther, born in 1970, studied Mechanical Engineering majoring in Materials Science and Engineering at TU Kaiserslautern University, Germany, from 1992 to 1997. There, he finished his PhD on the fatigue assessment of railway wheel steels in 2002, and his habilitation on physical measurement techniques for microstructural-based fatigue assessment and lifetime calculation of metals in 2007. At Schaeffler AG in Herzogenaurach, Germany, he took responsibility for Public Private Partnership within Corporate Development from 2008 to 2010. Since 2010, he has been Professor for Materials Test Engineering (WPT) at TU Dortmund University, Germany. His research portfolio includes determination of structure-property-relationships of metal- and polymer-based materials and components under fatigue loading from LCF to VHCF range, taking the influence of manufacturing and joining processes as well as service loading and corrosion deterioration into account.