International Journal of Precision Engineering and Manufacturing-Green Technology (2022) 9:1035–1048
https://doi.org/10.1007/s40684-021-00395-8

Online ISSN 2198-0810
Print ISSN 2288-6206

REGULAR PAPER

Production and Subsequent Forming of Chip-Based Aluminium Sheets Without Remelting

André Schulze[1] · Oliver Hering[1] · A. Erman Tekkaya[1]

Received: 26 May 2021 / Revised: 18 August 2021 / Accepted: 29 September 2021 / Published online: 22 October 2021

Abstract
Bent components and deep drawn cups are produced by direct usage of aluminium chips without melting following a new process chain: hot extrusion of aluminium chips to a cylindrical open profile, flattening, subsequent rolling and bending or deep drawing. The properties of the hot extruded chip-based AA6060 sheets are examined by tensile tests and microstructural investigations and the results are compared with those obtained from material extruded from conventional cast billets. The chip-based sheets were used to form components by bending or deep drawing. No significant differences between the bent components or deep-drawn cups made of chips and those from cast material are observed regarding their capability for further plastic forming operations. This makes the new process route a resource-efficient alternative for the production of aluminium sheet products.

Keywords Recycling · Chip extrusion · Solid state recycling · Metal forming · Sustainability · Aluminium scrap recycling

1 Introduction

The direct hot extrusion of cold-compacted aluminium chips is an energy and resource-efficient recycling process for the manufacturing of profiles which avoids the energy-intense remelting of the material. It was first patented by Stern [1]. Due to increasing demands regarding the reduction of CO_2-emissions in all engineering fields, including production, the research of the process has recently gained momentum. Other related processes for converting aluminium chips directly into profiles comprise screw extrusion [2] and friction stir extrusion [3]. Direct recycling routes of aluminium chips without melting lead to a significant reduction of energy and greenhouse gas emissions and gain higher material usage in comparison to energy intensive conventional recycling processes of aluminium scrap [4].

The energy use and the generated greenhouse gas emissions differ significantly, if conventional and direct recycling are compared for aluminium profile production. Based on a conventional recycling route covering secondary aluminium and hot extrusion the production of one tonne aluminium profile requires 30 GJ energy and generates 1520 kg CO_2-equivalents) [5]. This includes the thermal energies (i.e. fuels) and the purchased electricity necessary for refining and remelting. The emissions to air consist for example of nitrogen dioxide (NO_x) or chlorine (as Cl_2). In comparison, if only the extrusion process is considered, 16 GJ are required and 680 kg CO_2-equivalents are generated, which means the values can be cut by 47% and 55% respectively (Fig. 1) [5]. For this, the energy demand from renewable and non-renewable resources for the production of 1 ton of aluminium profile by a conventional hot extrusion process is assumed. The GHG-emissions cover all emissions to air which contribute to the global warming potential. In addition, a material loss of up to 17% can occur during the remelting of chips due to their high surface to volume ratio [6].

The basic process principle of hot extrusion of aluminium chips is equal to conventional extrusion, however using

✉ André Schulze
andre.schulze@iul.tu-dortmund.de

Oliver Hering
oliver.hering@iul.tu-dortmund.de

A. Erman Tekkaya
erman.tekkaya@iul.tu-dortmund.de

[1] Institute of Forming Technology and Lightweight Components, TU Dortmund University, Baroper Street 303, 44227 Dortmund, Germany

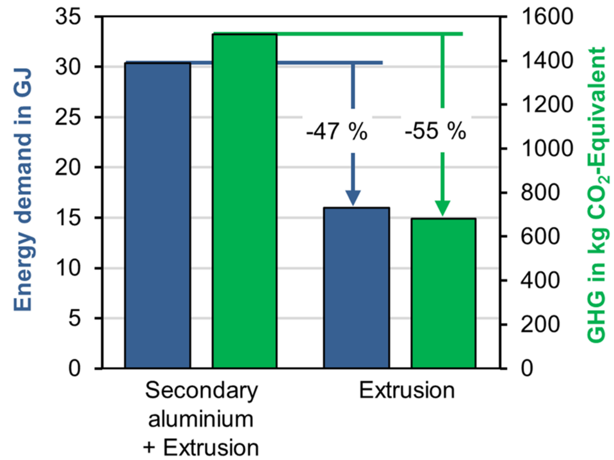


Fig. 1 Energy demand and greenhouse gas (GHG) emissions for the production of one tonne aluminium profile in the EU [5]

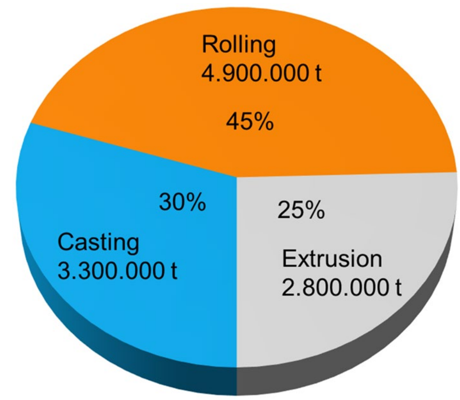


Fig. 2 Aluminium downstream industries in Europe [5]

compacted chip-based billets instead of cast billets. According to Gronostajski and Matuszak [7], the general process steps for the direct recycling of aluminium chips by chip extrusion are: compaction of the chips to chip-based billets, heating of the chip-based billets and extrusion. Additional challenges are introduced by the direct use of chips without melting due to the oxide layers covering each individual chip. These oxide layers prevent the aluminium welding and have to be broken during the process to ensure sound bonding. To achieve this, high strain as well as high hydrostatic pressure are necessary. The research done on chip extrusion dealt with identifying and adjusting the process parameters mandatory for a process success and the mechanical properties of the chip-based profiles. A process success is achieved if a macroscopically completely welded profile is produced. Several authors have identified the die design as the most significant influencing factor on the welding of the chips and thus the process success in direct hot extrusion of aluminium chips. Misiolek et al. [8] found that the use of simple flat-face dies leads to surface delaminations. Using porthole dies instead, Güley et al. [9] observed an improved chip bonding and better mechanical properties of the extrudates. The second most important influencing factor on the welding of the chips was identified as the extrusion ratio R, which is defined by

$$R = A_0/A_1 \quad (1)$$

where A_0 is the cross-section of the upset billet in the container, and A_1 is the cross-section area of the produced extrudate. A process success of the chip extrusion process is achieved when using higher extrusion ratios (flat-face die) [10] and also better mechanical properties in terms of higher strength and ductility are obtained [11]. The parameters of the extrusion process (billet temperature, extrusion speed, chip geometry) only have a minor influence on the chip welding and the process success. Tekkaya et al. [12] found, that within the range of industrially relevant chip geometries, no significant influence on the process success was present. The billet temperature was varied by Haase et al. [13] between 450 and 550 °C. Using different die types, no significant influence on the properties of the extrudates were observed. Tokarski [14] found, that an increased extrusion speed enables a good surface quality, whereas a lower extrusion speed led to visual defects on the extrudate. In general, the overall process success of chip extrusion is subject to the combination of all influencing factors, amongst which the die type and the extrusion ratio are the most significant parameters. With suitable parameter settings, satisfactory mechanical properties can be achieved, but these are limited and reach a maximum of 90% of the mechanical properties of profiles based on cast material.

By taking a look at the aluminium downstream industries in the European Union (Fig. 2), 45% of the aluminium is processed into rolled products (sheets) from which bent and deep-drawn components are produced. Areas of application are packaging, transportation, civil engineering or household goods. In comparison, extrusion products cover only 25% and cast parts 30%, meaning the majority of the parts are rolled products [5]. In 2017 over 26 million tons of old and new scrap was generated and reused. This scrap can be assigned to rolled or extruded scrap for example but a further differentiation concerning the type of scrap is not given [24]. It is difficult to quantify the proportion of chips in the total scrap, since the majority is usually prepared and further processed within one company, and thus no reliable data is available publicly. However, for different industries it is known how much of the input material is scrapped, for example in aerospace manufacturing 90% of the aluminium is turned into chips [25]. These numbers are strong arguments for research of the production of chip-based

Table 1 Chemical composition of the AA6060 aluminium alloy

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.44	0.21	0.02	0.05	0.39	0.00	0.011	0.01	0.01	98.86

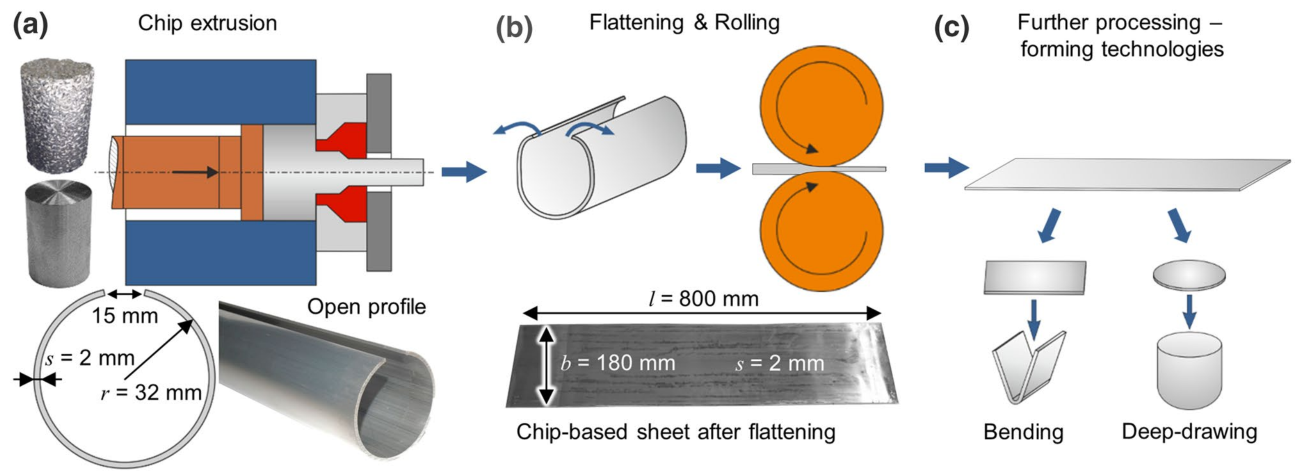


Fig. 3 New process chain for the production of chip-based sheets and further processing consisting of **a** extrusion to a cylindrical open profile **b** unfolding the profiles to sheets **c** forming technologies to produce bent parts and deep drawn cups

aluminium sheets and their further processing by forming operations using direct hot extrusion and rolling without melting.

1.1 Production of Metal Sheets by Hot Extrusion and Rolling

A first approach for the direct recycling of aluminium chips to sheet metal was investigated by Allwood et al. [15]. A bar was produced by chip extrusion and then rolled to final thickness. Between the rolling passes the sheets had to be edge trimmed. Attempts of drawing blanks into cups had limited success. Only one cup out of four could be produced successfully indicating a low formability of the sheets. Further work was done by Kore et al. [16]. Crushed aluminium AA6082 chips were compacted into slabs with a square cross-section (cold and hot) and then further processed by a hot rolling process. After annealing the sheets, cups with constant wall thickness could be produced by deep drawing. However, the authors could only produce small cups (d = 25 mm) because they were strongly limited by the dimensions of the sheets. Chino et al. [17] recycled magnesium AZ31 chips by extrusion and hot rolling. The chips were pressed into rectangular profiles and rolled perpendicular to the extrusion direction after heat treatment. Suzuki et al. [18] investigated the processes of extrusion and hot rolling of different chip shapes and chip sizes of the aluminium alloy AA6061. They produced rectangular profiles by extrusion which were hot rolled afterwards to reduce the thickness. Nevertheless, they had to mill off the surface to achieve profiles for further investigations. To enhance the profile width of extruded sheets, Gall et al. [19] extruded magnesium billets into open tube profiles which are directly flattened by a special device in a subsequent forming step. Grittner et al. [20] used a similar process combination and investigated the microstructure and texture which have an influence on the mechanical properties leading to a reduction of anisotropy.

The production of sheets by hot extrusion and subsequent rolling of aluminium chips investigated in literature is very limited concerning the dimensions of the sheets. Additional process steps during rolling are necessary to produce sheets making the production inefficient and the further processing of the sheets leads to an insufficient formability. In order to use the resource-saving direct recycling of chips for the largest market share of aluminium processing (sheets and their derived products) and allow for a further processing of the sheets, a new process chain is required which produces sheets in an efficient way and leads to properties of the sheets which allow for fabrication of products comparable to those made of cast material.

2 Materials and Process Steps

The aim of this paper is to introduce a new process chain consisting of hot extrusion of aluminium chips, flattening and rolling of the extruded open profiles to sheets and further forming operations (see Fig. 3). For this, the chips are characterized and the process steps chip extrusion, flattening and rolling are analysed and designed for sound bonding of the chips. The mechanical properties of the produced sheets are investigated and compared to cast material processed along the same process chain. Finally, chip-based bent components and cups are produced by bending and deep drawing, respectively, to assess the material's capacity to withstand further plastic forming processes, conventionally applied to produce a broad range of sheet-based aluminium products.

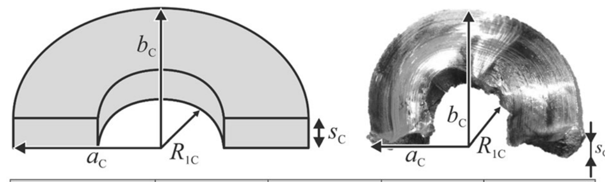
2.1 Chip Extrusion

For the production of chip-based sheets, aluminium alloy AA6060 was processed in five consecutive steps:

- Producing chips.
- Compaction of the chips to billets.
- Homogenization of the chip-based billets.
- Hot extrusion of the chip-based billets to open profiles.
- Flattening of the chip-based open profiles to sheets and rolling.

To evaluate the performance of the produced chip-based parts, the above shown processing steps were also conducted with cast billets of AA6060 to produce sheets and cups based on cast material as a reference. The AA6060 aluminium chips used in this work were produced by turning of the as-received homogenised cast bars. To prevent contamination of the chips, the turning process was carried out without the use of lubricant and the cast skin of the bars was first turned off and sorted out. The chemical composition of the cast AA6060, shown in Table 1, was analysed by apt Hiller GmbH by optical emission spectroscopy. The chips were produced by longitudinal turning with a cutting speed v_c = 400 m/min, a feed of f = 0.5 mm and a cutting depth of a_p = 2.25 mm. The produced chips were characterized in terms of their geometry and hardness. The majority of chips can be described as a half ellipse ring. In Fig. 4, the geometric approximation and a chip as well as the associated mean dimensions are shown. The average hardness of the chips after turning is 79 HV0.2. To allow handling of the machining chips during the hot extrusion process, the chips were compacted to chip-based billets. Compaction of the chips was conducted on an industrial briquette press RUF18.5 by RUF Maschinenbau GmbH & Co. KG. Chip-based billets with a diameter of 100 mm and a length of 110 mm were produced. The compaction loads were 3.7 t/cm^2 which is equal to 2905 kN.

The density of the chip-based billets was $\rho = 2{,}3$ g/cm^3 which is 85% of the density of cast aluminium ($\rho = 2.7$ g/cm^3). Because the chips were exposed to severe plastic deformation during machining and cold compaction the



Chip geometry	a_c	b_c	R_{1c}	s_c
Value in mm	3.85 ± 0.15	4.51 ± 0.44	1.9 ± 0.31	1.48 ± 0.09

Fig. 4 Chip geometry and average dimensions

chip-based billets were homogenized at 550 °C for 6 h according to Haase et al. [13] to remove the strain hardening. To ensure comparable initial material conditions, the cast billets were treated similarly. The extrusion die and process were designed in order to achieve a sound bonding of the chips by calculating the weld quality numerically. The extrusion trials of the chip-based and cast billets were carried out on a direct extrusion press (SMS Meer), which has a maximum extrusion force of 10 MN. Based on the findings in the state of the art, a porthole die was used to extrude a cylindrical open profile, with an outer diameter of 64 mm and a wall thickness of 2 mm. The container diameter was set as 106 mm, resulting in an extrusion ratio R = 24. The parameters billet temperature (550 °C), die/container temperature (450 °C) and the ram speed (2 mm/s) were set, to achieve a homogenous material flow inside the die [13]. The profiles were cooled in ambient air after extrusion. During the upsetting of the chip-based billet in the container a further compaction of the chips is conducted, leading to a density of 99.9 % before the material flows into the die. This was proved by porosity analysis via computer tomography on an extracted billet (Nikon XT H160, 75 voxels). A discard of 12 mm was sheared off after every extrusion cycle. Cast billets with a length of 270 mm were extruded with the same extrusion parameters used for the extrusion of chip-based billets (Fig. 3a).

2.2 Flattening and Rolling

In a second step the extruded profiles were flattened by unfolding the cylindrical open profiles to a sheet (Fig. 3b). For this the profiles were heated to 350 °C and the beginning of the profile was unfolded manually over a cone in order to attain a straight edge. Following the flattening takes place in a rolling mill by using the work rolls to unfold the cylindrical open profiles without a thickness reduction. The front face of the sheet was inserted into the roll gap, which was set to 2 mm corresponding to the wall thickness of the profile and thus the produced sheet. The speed of the work rolls was set to 7 rpm (roll diameter 200 mm). The profile is pulled into the roll gap and flattened along the longitudinal axis resulting in a flat aluminium sheet. Additionally, a part of the produced sheets was further rolled to reduce the thickness. It was carried out by cold rolling with a rolling speed of 7 rpm and multiple rolling steps. The relative thickness change ε_h is defined by

$$\varepsilon_h = (s_1 - s_0)/s_0 \quad (2)$$

where s_o is the initial thickness before rolling and s_1 is the thickness of the sheet after rolling. Final sheet thicknesses of s = 1.5 mm and s = 1.0 mm were achieved, resulting in nominal thickness reductions of $\varepsilon_h = 0.25$ and $\varepsilon_h = 0.5$. After rolling the sheets were soft annealed in order to eliminate the strain hardening and increase the materials formability for subsequent forming processes. Soft annealing was carried out at 340 °C for 2.5 h. Afterwards the sheets were cooled to 250 °C with a cooling rate of 30 K/h and then cooled in ambient air. The produced sheets were further processed by subsequent forming operations (Fig. 3c) to evaluate their capability of further plastic forming operations:

- Air bending to bent components.
- Deep drawing of the chip-based sheets to cups.

2.3 Bending and Deep Drawing

For the bending experiments, specimens with a length of l = 60 mm and a width of b = 30 mm were cut from the produced sheets. Air bending was applied on a Trumpf TrumaBend V 1300 bending machine. The bending was done perpendicular to the rolling direction of the sheets using a punch radius of r = 1 mm, a die width of 24 mm and a punch velocity of 2 mm/s.

Circular blanks were cut by laser cutting from the produced sheets with different thicknesses and then deep drawn, using a universal sheet metal testing machine Erichsen 142-20-Basic. For the cups a drawing punch diameter d_{punch} = 33 mm and different drawing dies (Ø = 35.8 – 36.6 mm) were used to produce cups with different deep drawing ratios. A blank holder force of 2 kN and a drawing punch speed of 1 mm/s were used. The experiments were conducted without lubrication.

2.4 Microstructural and Mechanical Analysis

The microstructure was characterized by light optical microscopy under polarized light on Zeiss Axio Imager.M1 m with Zeiss AxioCam MRc. Specimens for microstructure investigation were mechanically ground using SiC paper (grit 320, 800, 1200, 2000 and 4000 for 60 s each) and polished for 60 s with 3 µm, 1 µm and colloidal silica oxide. The polished specimens were electrolytically etched using Barker's reagent with a voltage of U = 25 V DC for 180 s on a Struers LectroPol-5.

The Vickers hardness was measured on a Shimadzu HMV-G21D with a Vickers diamond indenter in accordance with DIN EN ISO6507-1:2005 standard. A loading force of 1.961 N (i.e. HV0.2) and a holding time of 10 s at room temperature were applied. The hardness was measured three times on three different chips (nine measurements in total).

Flat tensile test specimens (gauge length l_0 = 20 mm, b_0 = 6 mm according to DIN 50125) were used and fabricated parallel to the extrusion direction by laser cutting from the profiles and sheets. They were pulled up to fracture. The tests were performed according to DIN EN ISO 6892-1 with a nominal strain rate of 6.7× 10^{-3}/s at room temperature on a Zwick/Roell Z250 tensile test machine.

2.5 Numerical Analyses

In order to acquire the necessary field quantities for the calculation of the weld quality of the chips, numerical analyses were carried out using the commercial finite element software Altair HyperXtrude. The die temperature was assumed constant at 450 °C and the initial billet temperature was 550 °C. Heat generation due to friction and plastic deformation (90 % of work for plastic deformation is transformed into heat) as well as heat transfer between the billet and the die was considered (heat transfer coefficient $\alpha = 3000$ W/m^2/K). Friction between the workpiece and the die was assumed as m = 1 (shear factor) according to experimental and numerical findings by Kloppenborg et al. [21]. The material in the welding chamber was meshed with tetrahedral elements with an average element length of l_e = 0.6 mm, the profile was meshed more finely with hexahedral elements with l_e = 0.25 mm. The aluminium alloy AA6060 was modelled as a rigid-viscoplastic material. To reduce the computational time a symmetry plane was used to calculate only one half of the profile.

3 Results and Discussion

3.1 Chip Extrusion

Prior to the extrusion experiments the porthole die was designed and simulated. The weld quality model for the prediction of the process success in direct hot extrusion of aluminium chips developed by Kolpak et al. [22] was used. This model allows for a prediction of the absolute bond strength σ_b as a function of the flow stress σ_f, hydrostatic pressure p and strain, according to

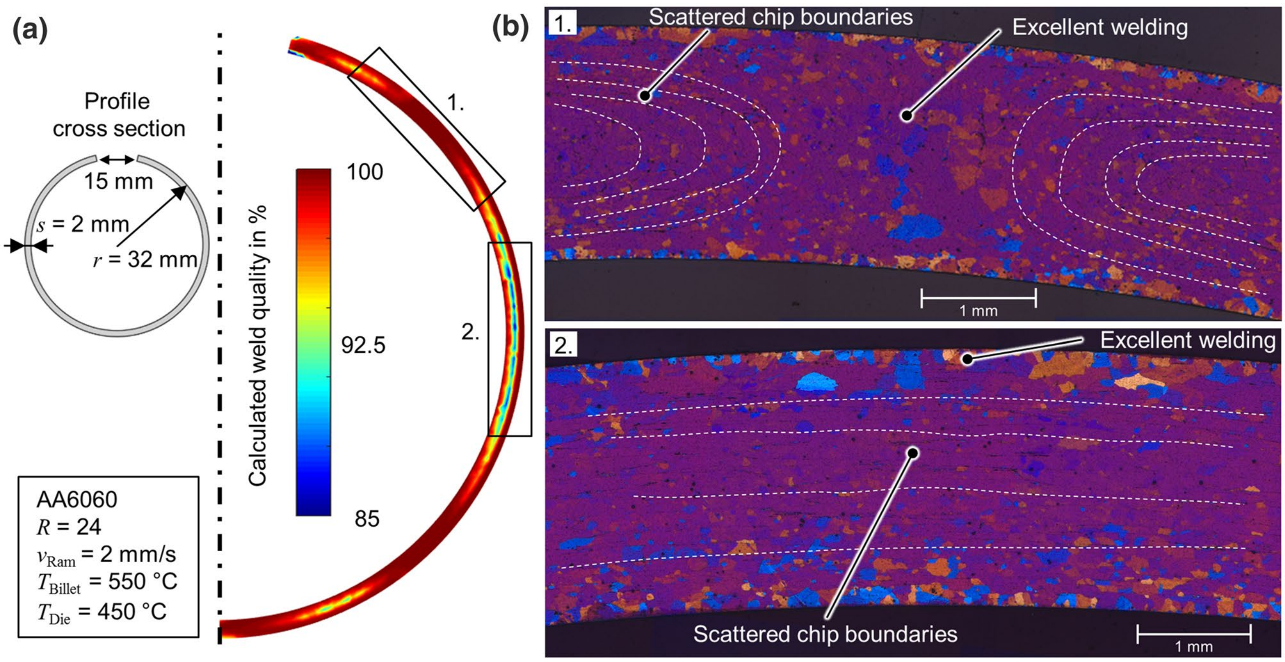


Fig. 5 **a** Contour plot of the calculated weld quality **b** microstructure of the extruded profile

$$\frac{\sigma_b}{\sigma_f} = \left(\frac{0.8}{\sigma_f}p\right) \cdot \nu \cdot \left(0.8\frac{p - p_{ex}}{\sigma_f}\right) \tag{3}$$

It defines the relevant stress for welding to be the hydrostatic pressure p. The surface expansion necessary to break oxides and allow base metal to flow through the resulting cracks is calculated by an additional factor ν. Therefore, it takes the effective plastic strain ε as the relevant strain into account. The pressure p_{ex} necessary to initiate micro extrusion of base metal through the cracks is subjected to a number of geometric as well as material dependent parameters. The details of the weld quality model and the necessary steps for the weld quality calculation can be taken from the publication. After the simulation of the extrusion process field quantities strain, pressure and flow stress were extracted. With these the weld quality of the chips over the profile cross section was calculated according to Eq. (3) and the generated contour plot was evaluated (Fig. 5a). In general, a high weld quality exists over the whole profile cross section. Especially in the surface region the weld quality amounts to over 95 % which was suggested by Kolpak et al. [22] to be necessary for a process success without delamination of the chips and defects on the profile surface. Across the wall thickness there is only a small area in the centre on the right side, where the calculated weld quality is below 90%. In the regions $\pm$ 45° a very high weld quality up to 100 % can be determined. This is due to the construction of the extrusion die. It uses support arms for the mandrel which split up the aluminium billet in four threads and cause a complex material flow. The aluminium has to move around the supporting arms of the mandrel. The chips experience higher strains due to the longer particle lines inside the porthole die before entering the welding chamber. This leads to a high surface enlargement of the chips and thus to a satisfactory welding.

Since the predicted surface-near weld quality distribution in the profile is above the reported threshold value of 95% a process success was expected and the extrusion experiments were carried out according to the numerical findings.

Extrusion profiles without defects could be produced from chips (see Fig. 3). They showed no difference to the reference profiles extruded from cast billets by comparing the geometry and surface quality. In order to review the results of the weld quality model and to analyse the welding of the chips microscopic images were created. In Fig. 5b the two significant regions derived from the weld quality calculation are analysed in the microscopic images. In the region of the supporting arm of the mandrel where a high weld quality was estimated no chip boundaries are visible (centre). Dispersed grains can be spotted across the wall thickness. In this region recrystallized grains beyond initially present weld lines indicate a good welding of the chips. Scattered, former chip boundaries on the left hand and right hand side can be identified. These boundaries are arranged along the marked lines. This underlines the assumption that the chips travel around the supporting arms of the mandrel and weld behind them. The microstructure is in accordance with the calculated weld quality. The second image shows the region with the lowest calculated weld quality in the centre of the profile wall thickness. In the surface region the chips show a sound welding as no chip boundaries are visible and fine and dispersed grains exist. In the centre of the wall thickness scattered chip boundaries can be seen. In some cases, the grain boundaries extend over the chip boundaries, representing a sufficient welding. In summary, the microstructural findings show a sufficient agreement with the calculated weld quality. The weld quality model obtains an accurate prediction of the chip welding and a sound welding over the profile cross section.

The mechanical properties of the extruded profiles were investigated by tensile tests, since the strength depends on the bonding quality between the individual chips.

To assess possible inhomogeneities of the weld quality, tensile test specimens were extracted from five different positions over the cross section of the extruded profiles (see Fig. 6a). The results for yield strength and ultimate tensile strength derived from six tensile tests for each position are shown in Fig. 6b. The results indicate no difference for neither the yield strength nor the ultimate tensile strength regardless of the underlying extraction position. The mechanical properties over the profile cross section are homogeneous. The overall high weld quality is high as sound welding of the chips found in the microstructure. In addition, the low data scatter indicate that the mechanical properties are also constant along the profile length.

By comparing the tensile test results of chips extruded through the porthole die with those of material extruded with the same parameters (Fig. 7), it is found, that both the yield strength as well as the ultimate tensile strength are about 10% lower, which indicates a nearly perfect bonding quality between the individual chips. Likewise, the data scatter is very low. The 10% difference between chip-based and cast-based profiles are due to a lack of welding between the chips which occurs mainly in the centre region of the profile and as well as the slightly different microstructure. This is clearly visible in the microscopic images (Fig. 5b). Hence, the die and process design lead to a high bonding quality of the chips which results in macroscopic comparable profiles with sufficient mechanical properties.

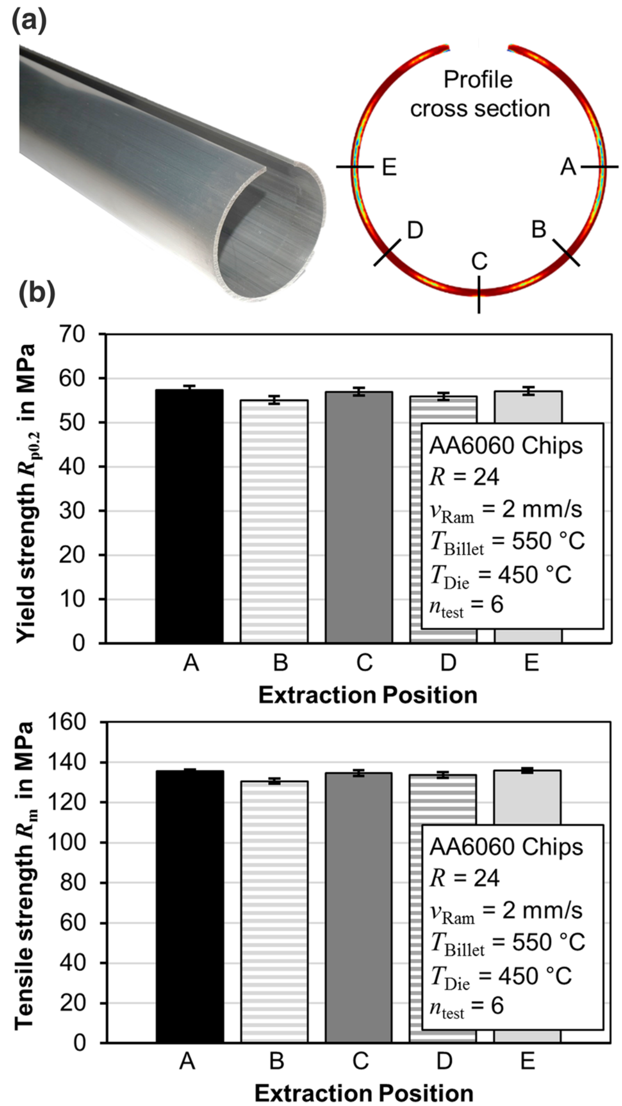


Fig. 6 **a** Position of the tensile test specimens **b** mechanical properties for the different extraction positions of chip-based profiles

3.2 Flattening and Rolling

The extruded open profiles were unfolded and flattened to create chip-based sheets with a width of b = 180 mm, a length of l = 800 mm and a thickness of s = 2 mm (Fig. 8a). A part of the sheets was further rolled in order to reduce the thickness. It is expected that a further reduction of the sheet thickness by rolling enhances the mechanical properties. These sheets were also used for the further processing in bending and deep drawing processes. Based on the knowledge that for the welding of the chips strain and pressure are the decisive parameters, it is expected that the rolling process contributes to an increase of the welding of the chips. Within the rolling gap the sheet thickness is reduced and the length is increased resulting in strain and pressure existing simultaneously.

The sheets were rolled with a thickness reduction of $\varepsilon_h = 0.25$ resulting in a final thickness of s = 1.5 mm and $\varepsilon_h = 0.5$ resulting in a final thickness of s = 1.0 mm (Fig. 8b). The thickness reduction was conducted in two and four rolling passes respectively, each accounting for a thickness reduction of 0.25 mm per pass. The sheets are characterized by micrographs and tensile test.

Micrographs of the chip-based flattened sheet (s = 2.0 mm) and the rolled sheet with a thickness of s = 1.0 mm ($\varepsilon_h = 0.5$) are shown in Fig. 9. The images are taken in longitudinal direction (parallel to the rolling direction). A sound

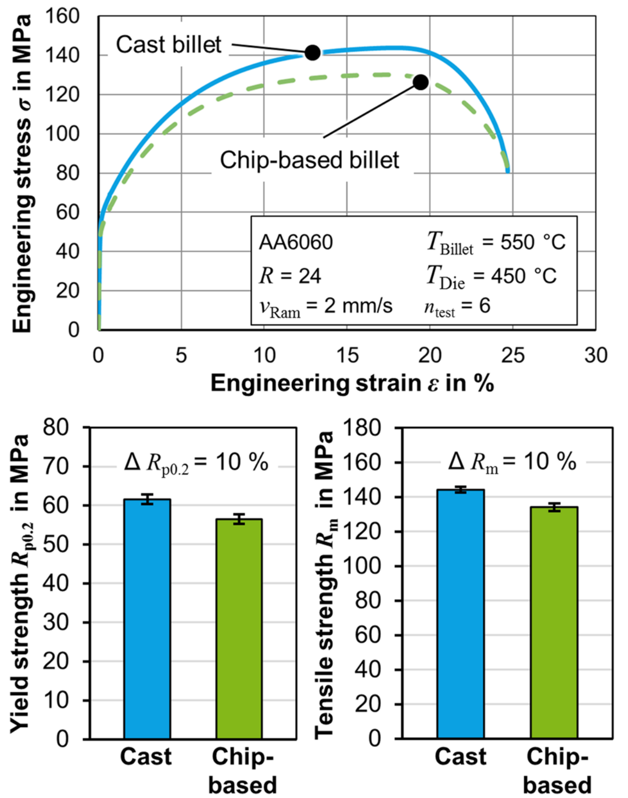


Fig. 7 Comparison of mechanical properties of chip-based and cast-based profiles

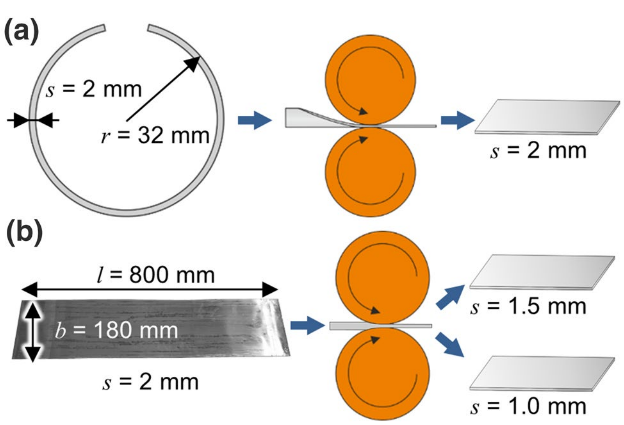


Fig. 8 **a** Flattening of extruded open profile **b** cold rolling of sheets

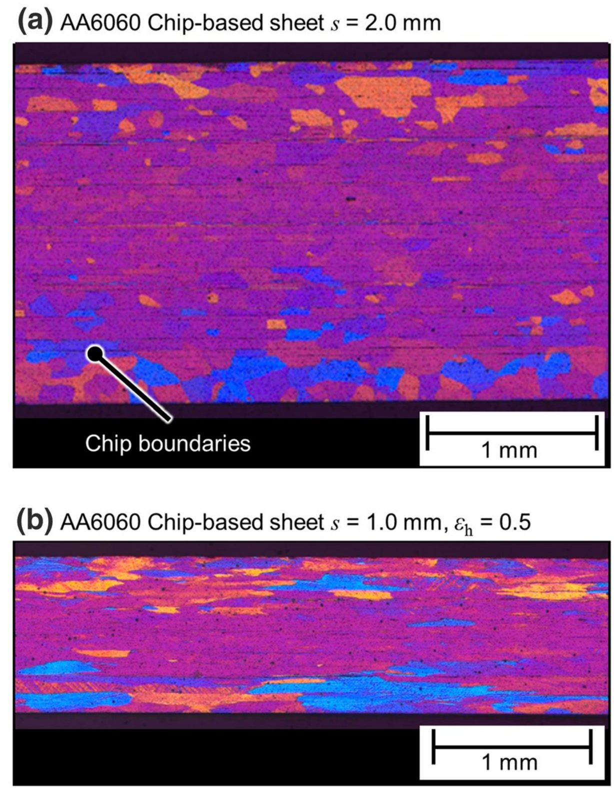


Fig. 9 Microstructure of chip-based sheets **a** flattened (s = 2 mm) **b** after rolling (s = 1 mm, ε_h = 0.5)

welding of the chips in the surface region is visible for the flattened sheet. Nevertheless, long chip boundaries extend parallel to the surface and are present over the entire sheet thickness. Beyond the surface region some grains do not extend over the chip boundaries. After rolling the welding and microstructure differs for the chip-based sheet with s = 1 mm thickness. Dispersed and stretched grains due to the rolling process can be spotted. Less chip boundaries are visible and the ones visible are shorter and thinner compared to the flattened sheet (s = 2.0 mm). Recrystallized grains beyond initially present weld lines indicate an enhanced welding of the chips. The enhanced welding is expected to improve the mechanical properties which are investigated in the next section.

The tensile test results show a strong influence of the rolling (Fig. 10). The yield strength of the sheets increases after rolling by approximately 90 % almost independently of the rolling reduction and similarly for profiles obtained from chips and from cast billets. This effect is attributed to strain hardening. Due to this also the ductility of the sheets decreases. The fracture strain obtained in the tensile tests decreases by 60 % for ε_h = 0.25 and 75 % for ε_h = 0.5 due to the large accumulated strain.

As expected the stress-strain curves of the chip-based sheets are below the ones of the cast material. The results also reveal that the mechanical properties of the chip-based sheets increase after the rolling process. The difference between chip-based sheets and the ones made from cast material can be lowered from 10 % initial to approximate 6 % after rolling. This justifies the assumption that rolling improves the welding quality of the chips.

The metal sheets were soft annealed subsequent to rolling to reduce the effect of strain hardening and increase the

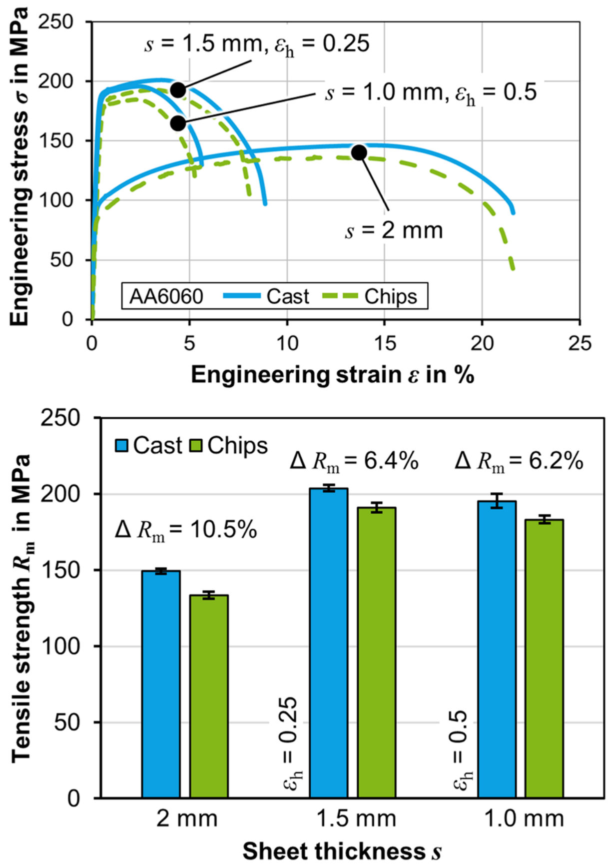


Fig. 10 Mechanical properties of the flattened and rolled sheets (averaged over six tests)

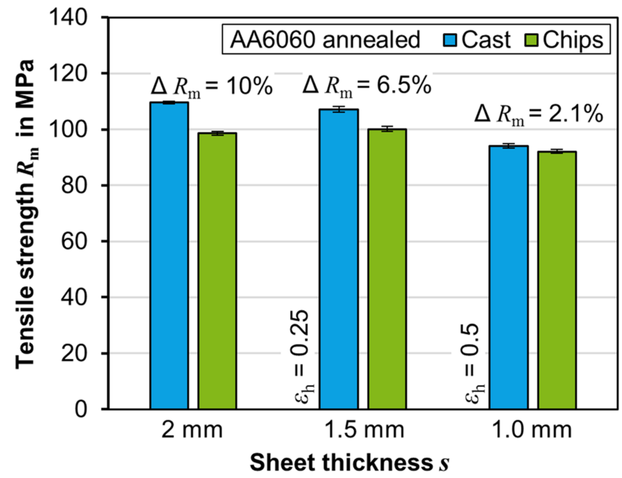


Fig. 11 Mechanical properties of the annealed sheets (averaged over six tests)

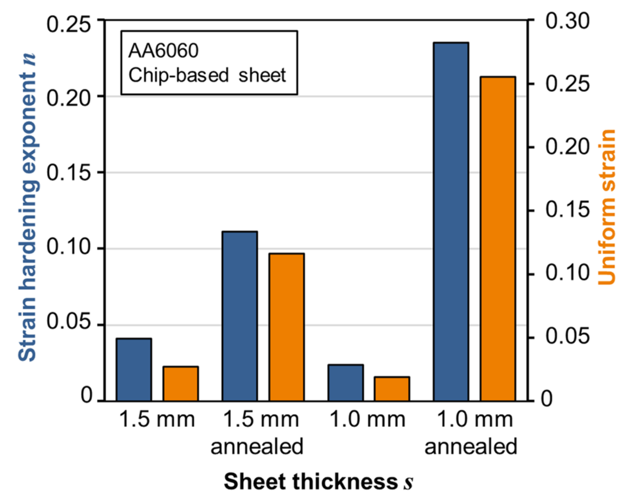


Fig. 12 Material parameters to evaluate the capability for further forming processes of the chip-based sheets

materials formability for subsequent forming processes. The goal was to achieve sheets with high strain hardening potential and high ductility suitable for further forming operations. The tensile test results after soft annealing show that the strain hardening caused by rolling has been eliminated by the heat treatment (Fig. 11). The tensile strength of the initial sheet ($s = 2$ mm) and the 25 % reduced sheet ($s = 1.5$ mm) show similar values for the chip-based as well as the cast material. The tensile strength of the 50 % reduced sheet ($s = 1$ mm) are slightly lower which means the heat treatment has led to a softening of the material. Nevertheless, the enhancement of the mechanical properties due to the improved welding of the chips after rolling are validated by the findings. The differences between chip-based sheets and the cast sheets can be lowered from 10 to 6.5% ($\varepsilon_h = 0.25$, $s = 1.5$ mm) to 2.1% ($\varepsilon_h = 0.5$, $s = 1$ mm).

Addressing the enhancement of the mechanical properties regarding the formability the strain hardening exponent n and the uniform elongation for the chip-based sheets in rolled and soft annealed condition are shown in Fig. 12. According to Lange [23] these values should be maximized since the tendency of the material to local necking during forming depends directly on the hardening exponent. After rolling ($s = 1.5$ mm, $\varepsilon_h = 0.25$ and $s = 1.0$ mm, $\varepsilon_h = 0.5$) the values are very low due to strain hardening After soft annealing the n values und uniform elongation increase, though the values for the 1.5 mm sheet are only half of the values of the 1.0 mm sheet. It is assumed that the improved chip welding in the rolled sheets ($s = 1.0$ mm) leads to an enhanced recrystallization in the centre causing an increased formability, which is verified by the deep drawing experiments.

3.3 Bending

To assess the capability of further plastic forming operations of the chip-based sheets air bending experiments were carried out. For this a V-shaped profile was bent. The forming,

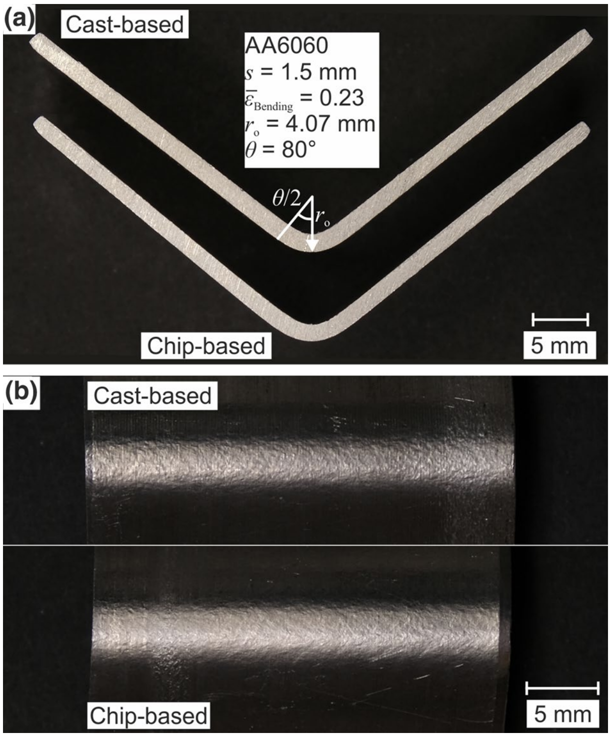


Fig. 13 Air bending of s = 1.5 mm sheets **a** comparison of shape b) surface at the outer fiber

failure and spring back behaviour compared to the cast-based sheets was analysed to encounter if there is a difference. In Fig. 13 the results of the air bending experiments are shown for the sheets with a thickness of s = 1.5 mm ($\varepsilon_h = 0.25$). Illustrated are the results for chip-based as well as the cast-based sheets. It can be seen that V-shaped profiles were successfully bent from both materials.

The punch force is 20% lower for the bending of the chip-based sheets. This is related to the chip boundaries visible in the microsections and the related missing welding of the chips in the inner regions of the profile as well as the corresponding lower flow stress. A bending radius of the outer fiber r_o = 4.07 mm for the 1.5 mm sheets and r_o = 2.46 mm for the 1.0 mm sheets was obtained. The values are 13% (1.5 mm) and 2.5% (1.0 mm) above the minimal achievable bending radius according to Lange [23]. It corresponds to an effective strain $\overline{\varepsilon}_{Bending}$ = 0.23 for the 1.5 mm sheet and $\overline{\varepsilon}_{Bending}$ = 0.26 for the 1.0 mm sheet (assuming isotropic material behavior and idealized plane strain bending). The maximum deviation of the radii between chip-based and cast-based parts is 2%. Matching geometrical values between chip-based and cast-based sheets reveal no difference since the bending angle is equal for both (1.5 mm sheet: $\theta = 80°$; 1.0 mm sheet: $\theta = 70°$). The comparison of the bending radius and the shape of the bent profiles after spring back reveals that the forming for both chip-based and cast-based profiles is equal (Fig. 13a).

The surface at the outer fibre of the chip-based and cast-based bent profiles are free from macroscopic cracks or other failures. The surface for both sheets show some orange peel which is a visual defect resulting from large grains at the surface of the sheets (Fig. 13b). This only influences the surface and does not limit the forming of the sheets. Nevertheless, an enhanced heat treatment can solve this by creating smaller grains. In general, the orange peel appears for all investigated samples. It can be stated that there are no differences between chip-based and cast-based bent profiles.

Since the chip-based sheets allow for further forming operations and due to the successful bending experiments, the deep drawing experiments were conducted to investigate if the production of cups is possible as well.

3.4 Deep Drawing

To increase the complexity of stress states during further forming operations and assume if the chip-based sheets can cope with these, deep drawing experiments were conducted. For the deep drawing of the soft annealed sheets three different circular blanks (d_0 = 55 mm, d_0 = 60 mm, d_0 = 65 mm) were used to achieve different deep drawing ratios ($\beta = 1.67$, $\beta = 1.81$, $\beta = 1.96$). The circular blanks were cut from the sheets with a thickness of s = 1.5 mm as well as s = 1 mm. Table 2 lists the investigated combinations of process parameters. The deep drawing ratios were chosen to start from a moderate one ($\beta = 1.67$) and end with a high ratio ($\beta = 1.96$) to identify the range within cups can be produced from chip-based sheets. According to Lange [23] for aluminium sheets the maximum deep drawing ratio is $\beta = 2.1$. Cups without defects were manufactured from the sheets with a thickness of s = 1 mm with a deep drawing ratio of $\beta = 1.67$. Chip-based as well as cast-based cups were successfully deep drawn from both materials showing no differences of the external appearance. The cups deep drawn from the sheets

Table 2 Parameters of the deep drawing experiments

Parameter	Variation		
Drawing die	$\varnothing$ = 35.8 mm, r = 1.2	$\varnothing$ = 36.2 mm, r = 1.4	$\varnothing$ = 36.6 mm, r = 1.6
Deep drawing ratio $\beta = d_0/d_{punch}$	$\beta = 1.67$	$\beta = 1.81$	$\beta = 1.96$
Sheet thickness	s = 1 mm	s = 1.5 mm	

with a thickness of s = 1 mm and a deep drawing ratio of $\beta = 1.81$ are shown in Fig. 14. The experiments were successful for both materials as well.

For a deep drawing ratio of $\beta = 1.96$ a bottom crack occurs for the chip-based and the cast-based cups (Fig. 15). This means the process success is equal for chip-based and cast-based material and no difference can be made between the distinct cups. A difference in external appearance cannot be determined either. Concluding cups based on chips equal to conventional material can be produced.

The experiments with the sheets with 1.5 mm thickness show similar results. For a deep drawing ratio of $\beta = 1.67$ cups were successfully produced (Fig. 16), however for a deep drawing ration of $\beta = 1.81$ bottom cracks occur (Fig. 17). Also in the experiments with the 1.5 mm sheets there is no difference between the chip-based and the cast-based cups.

The failure occurs for both materials at a deep drawing ration of $\beta = 1.81$. The outer appearance of both cups is equal and no difference can be made.

The results are in good accordance with the mechanical properties especially the strain hardening exponent n and the uniform elongation of the sheets. Since the values for the 1.0 mm sheets are twice as high as for the 1.5 mm sheets after soft annealing, enhanced formability can be confirmed by the deep drawing experiments as the higher deep drawing ratio can only be achieved with the 1.0 mm sheets. In further investigations the heat treatment of the sheets will be adjusted to increase the formability of the sheets and to determine the maximum achievable deep drawing ratio. The experiments show the capability of the chip-based sheets to

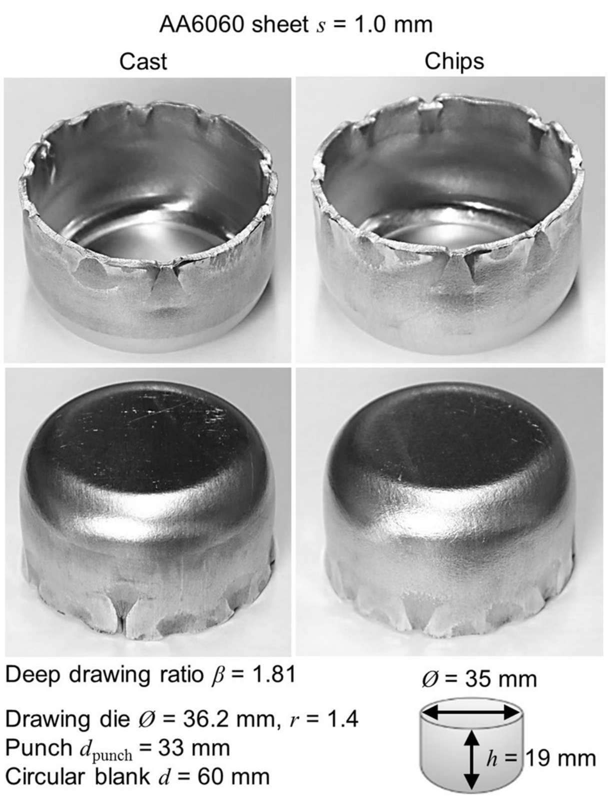


Fig. 14 Results of deep drawing experiments of soft annealed sheets s = 1.0 mm for a deep drawing ratio $\beta = 1.81$

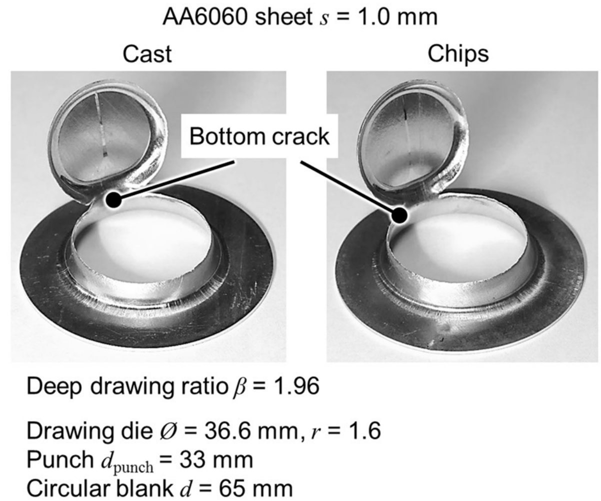


Fig. 15 Results of deep drawing experiments of soft annealed sheets s = 1.0 mm for a deep drawing ratio $\beta = 1.96$

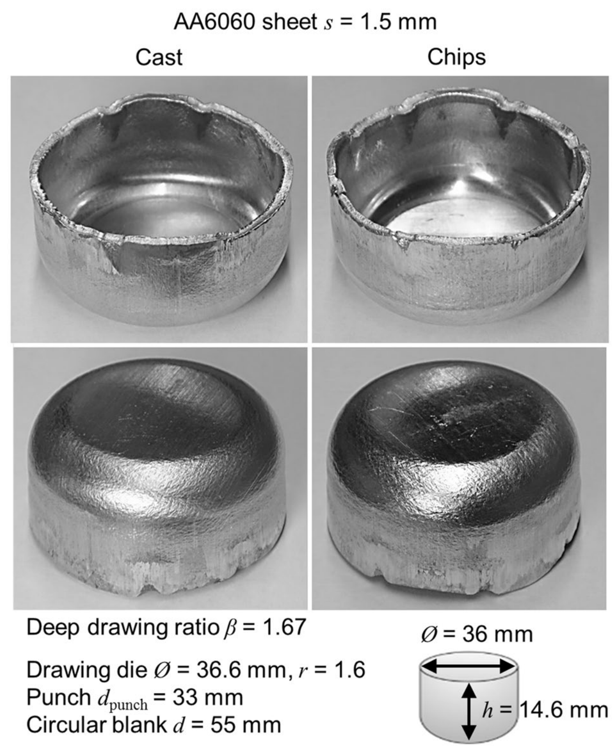


Fig. 16 Results of deep drawing experiments of soft annealed sheets s = 1.5 mm sheets for a deep drawing ratio $\beta = 1.67$

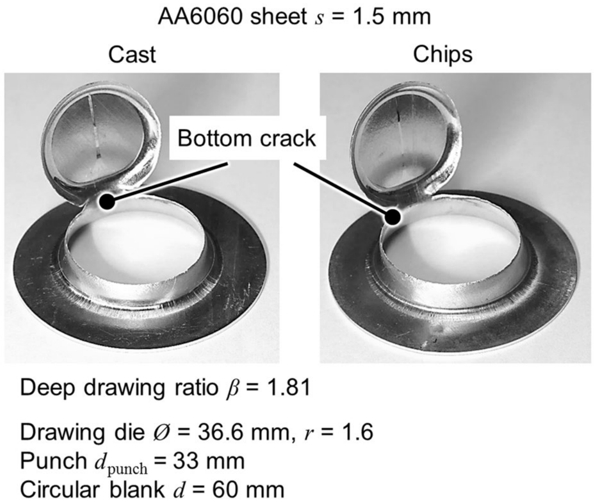


Fig. 17 Results of deep drawing experiments of soft annealed sheets s = 1.5 mm sheets for a deep drawing ratio $\beta = 1.81$

form basic deep drawn products which can be found in the packaging industry for example. Tins and boxes for cosmetic products without high requirements regarding their mechanical properties could be a general field of application.

4 Conclusions

Bent components and deep drawn cups made of aluminium chips were produced without melting by the novel process route consisting of direct hot extrusion of aluminium chips and subsequent flattening and rolling of the extruded profiles. Chip-based sheets can be efficiently produced by the introduced process steps capable to withstand further forming operations which allow for a production of components. The results extend the opportunities of direct recycling of aluminium chips to a wide range of products, contributing to saving energy, resources and lowering greenhouse gas emissions as compared to the conventional melting based aluminium recycling route to produce sheet-based products.

AA6060 aluminium chips were cold compacted and the extrusion process was designed in order to achieve a sound bonding of the chips to ensure a process success. The weld quality model by Kolpak et al. [22] was used to predict the weld quality of the chips in the final profile and determine the optimal process parameters. To validate the results of the chip weld quality model, the microstructure of the extruded profiles was investigated. A good agreement of the predicted weld quality with the extrusion experiments was found. The mechanical properties are constant over the complete cross section. A subsequent thickness reduction of the chip-based sheets by rolling leads to an improvement of the mechanical properties resulting in lowering the differences to conventional cast-based material. The improvement of chip welding is verified by microstructural analyses. Three important conclusions can be made regarding the capability of further plastic forming operations of chip-based aluminium sheets:

- The welding of the chips is sufficient enough to produce sheets based on aluminium chips and successfully perform different forming operations to produce end products without material failure.
- Air bending to V-shaped profiles produces equally defect-free parts possessing similar bending radii and bending angles.
- Deep drawing of cups with different deep drawing ratios is possible and no macroscopic differences are observed between cast-based and chip-based cups. In both cases the process limits are equal and only the deep drawing ratio is limiting the results.

In the future, a further investigation of the ongoing processes of welding during rolling will be conducted to explain the improvement of the chip-weld quality observed after rolling. The anisotropy and the forming limits of the chip-based sheets will be identified in order to produce more complex components. In addition, a comparison to conventional sheet metal produced by casting und rolling will be made. For the applicability of the process chain in industrial scale, questions about the integration of the compaction step and the handling of the chips have to be answered. Moreover, the size of the plant especially the extrusion press has a direct influence on the dimensions of the sheets that can be produced. The main challenges will be the organization of the acquisition and preparation of chips and the adjustment of the existing plant equipment.

Acknowledgements This work is based on investigations of the research project "Production of sheets by hot extrusion of aluminium chips" funded by the German Research Foundation (DFG, Project number: 437426733). Its financial support is greatly acknowledged.

Funding Open Access funding enabled and organized by Projekt DEAL. The research leading to these results was funded by the German Research Foundation (DFG, Project number: 437426733).

Availability of data and material Data can be provided by the corresponding author.

Code availability Not applicable.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

1. Stern, M. (1945). Method for treating aluminum or aluminum alloy scrap, U. S. Patents 2391752.
2. Widerøe, F., & Welo, T. (2013). Using contrast material techniques to determine metal flow in screw extrusion of aluminium. *Journal of Materials Processing Technology*, 213, 1007–1018. https://doi.org/10.1016/j.jmatprotec.2012.11.013.
3. Tang, W., & Reynolds, A. P. (2010). Production of wire via friction extrusion of aluminum alloy machining chips. *Journal of Materials Processing Technology*, 210, 2231–2237. https://doi.org/10.1016/j.jmatprotec.2010.08.010.
4. Duflou, J. R., Tekkaya, A. E., Haase, M., Welo, T., Vanmeensel, K., Kellens, K., et al. (2015). Environmental assessment of solid state recycling routes for aluminium alloys. Can solid state processes significantly reduce the environmental impact of aluminium recycling? *CIRP Annals, 64,* 37–40. https://doi.org/10.1016/j.cirp.2015.04.051.
5. EA—European Aluminium Environmental Profile Report, lifecycle inventory data for aluminium production and transformation processes in Europe. Brussels, Belgium.
6. Grayson, J. (2017). Reducing Melt Loss and Dross Generation. *Light Metal Age*, 75, 32–35
7. Gronostajski, J., & Matuszak, A. (1999). The recycling of metals by plastic deformation: an example of recycling of aluminium and its alloys chips. *Journal of Materials Processing Technology*, 92-93, 35–41
8. Misiolek, W. Z., Haase, M., Ben Khalifa, N., Tekkaya, A. E., & Kleiner, M. (2012). High quality extrudates from aluminum by new billet compaction and deformation routes. *CIRP Annals*, 61, 239–242. https://doi.org/10.1016/j.cirp.2012.03.113.
9. Güley, V., Güzel, A., Jäger, A., Khalifa, N. B., Tekkaya, A. E., & Misiolek, W. Z. (2013). Effect of die design on the welding quality during solid state recycling of AA6060 chips by hot extrusion. *Materials Science & Engineering, 574,* 163–175. https://doi.org/10.1016/j.msea.2013.03.010.
10. Fogagnolo, J. B., Ruiz-Navas, E. M., Simón, M. A., & Martinez, M. A. (2003). Recycling of aluminium alloy and aluminium matrix composite chips by pressing and hot extrusion. *Journal of Materials Processing Technology*, 143-144, 792–795
11. Güley, V. (2014). Recycling of aluminum chips by hot extrusion. Dissertation TU Dortmund University.
12. Tekkaya, A. E., Schikorra, M., Becker, D., Biermann, D., Hammer, N., & Pantke, K. (2009). Hot profile extrusion of AA-6060 aluminum chips. *Journal of Materials Processing Technology*, 209, 3343–3350. https://doi.org/10.1016/j.jmatprotec.2008.07.047.
13. Haase, M., Khalifa, N. B., Tekkaya, A. E., & Misiolek, W. Z. (2012). Improving mechanical properties of chip-based aluminum extrudates by integrated extrusion and equal channel angular pressing (iECAP). *Materials Science and Engineering A, 539,* 194–204. https://doi.org/10.1016/j.msea.2012.01.081.
14. Tokarksi, T. (2016). Mechanical properties of solid-state recycled 4xxx aluminum alloy chips. *Journal of Materials and Performance, 25,* 3252–3259. https://doi.org/10.1007/s11665-016-2194-1.
15. Allwood, J. M., Cullen, J. M., Cooper, D. R., Milford, R. L., Patel, A. C. H., Carruth, M. A., & McBrien, M. (2010). Conserving our metal energy—avoiding melting steel and aluminium scrap to save energy and carbon. WellMet2050, University of Cambridge.
16. Kore, A. S., Nayak, K. C., & Date, P. P. (2017). Formability of aluminium sheets manufactured by solid state recycling. *Journal of Physics Conference Series, 896,* 12007. https://doi.org/10.1088/1742-6596/896/1/012007.
17. Chino, Y., Kobata, M., Shimojima, K., Hosokawa, H., Yamada, Y., Iwasaki, H., & Mabuchi, M. (2004). Blow forming of Mg alloy recycled by solid-state recycling. *Materials Transactions, 45,* 361–364. https://doi.org/10.2320/matertrans.45.361.
18. Suzuki, K., Huang, X. S., Watazu, A., Shigematsu, I., & Saito, N. (2007). Recycling of 6061 aluminum alloy cutting chips using hot extrusion and hot rolling. *MSF*. https://doi.org/10.4028/www.scientific.net/MSF.544-545.443.
19. Gall, S., Müller, S., & Reimers, W. (2011). Extrusion of magnesium sheets with increased width. In Proceedings of the 10th International Conference on Technology of Plasticity (ICTP), *Steel Research International,* Special Edition, Aachen, Germany, 25–29 September 2011; pp. 286–290.
20. Grittner, N., Engelhardt, M., Neumann, A., Klose, C., & Hübner, S. (2014). A novel process for producing large scale Mg-sheets. *Magnesium Technology, 2014,* 289–292. https://doi.org/10.1007/978-3-319-48231-6_55.
21. Kloppenborg, T., Schwane, M., Ben Khalifa, N., Tekkaya, A. E., & Brosius, A. (2012). Experimental and numerical analysis of material flow in porthole die extrusion. *Key Engineering Materials*, 491, 97–104. https://doi.org/10.4028/www.scientific.net/KEM.491.97.
22. Kolpak, F., Schulze, A., Dahnke, C., & Tekkaya, A. E. (2019). Predicting weld-quality in direct hot extrusion of aluminium chips. *Journal of Materials Processing Technology*, 274, 116–294. https://doi.org/10.1016/j.jmatprotec.2019.116294.
23. Lange, K. (1975). *Lehrbuch der Umformtechnik, Band 3: Blechumformung*. Springer. https://doi.org/10.1007/978-3-662-22089-4.
24. Bertram, M., Ramkumar, S., Rechberger, H., Rombach, G., Bayliss, C., Martchek, K. J., & Liu, G. (2017). A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. *Resources, Conservation and Recycling., 125,* 48–69.
25. Allwood, J. M., & Cullen, J. M. (2015). *Sustainable Materials, Without the hot air. Making Buildings, Vehicles and Products Efficiently and with less New Material*. UIT Cambridge.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

André Schulze received his B.Sc. andM.Sc. degrees from the Institute of Forming Technology and LightweightComponents (IUL), Technical University Dortmund, Germany, in 2014 and 2016respectively. Since 2016, he is working towards a Ph.D. degree in the field ofchip extrusion in the department of bulk metal forming.

Oliver Hering received his M.Sc. degree inmechanical engineering from TU Dortmund in 2015 and is since then working as are-searcher at the IUL in different forming-related areas. In 2020 he obtained aPh.D. at the Institute of Forming Technology and Lightweight Components (IUL),Technical University Dortmund. He currently serves as the head of thedepartment of bulk metal forming at the IUL.

A. Erman Tekkaya received his B.Sc. (1979) andM.Sc. (1980) degrees from the Mechanical Engineering Department, Middle EastTechnical University (METU), Ankara/Turkey. In 1985 he obtained a Ph.D. at theInstitute of Forming Technology, University of Stuttgart, Germany. Since 2007,he is the Professor and Head of Institute of the IUL at the TechnicalUniversity Dortmund, Germany. He is a member of several forming technologyexpert committees and he has contributed over 800 publications in journals andconference proceedings.