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Comparison of Friction Extrusion Processing from Bulk and Chips of Aluminum-Copper Alloys

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Abstract. Friction extrusion processing describes the extrusion of metallic materials via severe plastic deformation imposed by friction-induced heat and shear strain. The process features relative rotational movement between die and feedstock material, resulting in complex shear introduction affecting local thermal and material flow conditions. While the processing of powders, chips and bulk material for improvement of extrudate properties has been studied independently, this work focuses on the direct comparison between the friction extrusion of bulk material and chips of AlCu10 under identical processing conditions. Analysis of machine response and microstructure in the extruded wires allows for first conclusions, identifying characteristics and requirements for friction extrusion processing from different feedstock materials.

Introduction

Developed in the early 1990s at TWI and first patented by Thomas et al. [1] in 1993, the forming of metallic materials under pressure and shear presents a fairly novel processing method with distinct advantages. The friction extrusion processing (FEP), schematically shown in Fig. 1, takes place under axial force exerted by a die onto contained material, while continuous relative rotation leads to localized heat generation. The feedstock material in shape of billets, chips or powder, plasticizes and consolidates under friction-induced heating and the enforced shearing. The material undergoes severe plastic deformation with beneficial impact on the microstructural evolution during extrusion, while the extrudate is shaped into a wire by the die orifice.

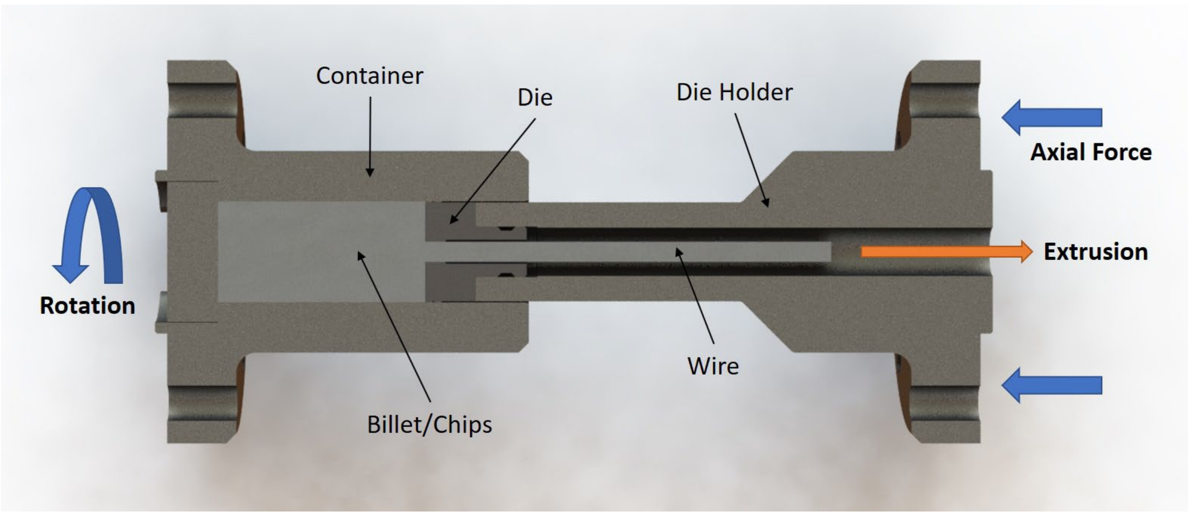

Fig. 1: Sketch of FEP setup, including relevant components and main control factors.

For alloys not easily extruded by conventional means, FEP could improve the manufacturing approach, as most recently demonstrated by Whalen et al. [2] for the shear assisted processing and extrusion of tubing from AA 7075, surpassing conventional extrusion rates and providing superior tensile properties. Whalen et al. [3] also reported a significant improvement in strength-ductility relationship for the production of wires from modified aluminum powder, related to the preservation of nanoscale particles throughout FEP.

The FEP from aluminum and magnesium chips is of particular interest for recycling purposes, as it presents an energy efficient alternative to remelting and casting. Compared to conventional extrusion, the localized heat generation makes a preheating of the raw material unnecessary. The high amount of strain induced by the shear motion leads to significant reduction in required axial force, as demonstrated by Widerøe et al. [4] for the consolidation of aluminum alloy granulate, further contributing to the energy efficiency of FEP. The effect of rotational speed and extrusion ratio on the mechanical properties of friction stir extruded wires from AZ31 magnesium alloy was investigated by Buffa et al. [5], identifying rotation as key process parameter and correlating low process temperatures and high strain with defect formation.

The knowledge about the behavior of Al-Cu alloys in FEP of wires, however, is limited so far. Tang and Reynolds [6] described the FEP of wires from AA 2050 and AA 2195 machining chips and reported an equiaxed, recrystallized microstructure in the extruded wires, yielding homogeneous hardness and good bend ductility. The processing limits, apparent by either cold tearing or a form of hot cracking, were suspected to correlate with the extrusion temperature. Hosseini et al. [7] reported similar findings for FEP from AA 2025 chips, emphasizing the effect of process parameters on void formation between chips. The FEP of wires from bulk AA 2050 material, investigated by Baffari et al. [8], showed processability regardless of heat treatment of the billet and was able to generate equiaxed, refined grains across the extrudate. In agreement with the findings for aluminum chips [6, 7], excessive thermal input via high extrusion force and high rotational speed was identified as processing limitation leading to hot cracking and massive grain growth in the extruded wire. Baffari et al. [9] also demonstrated feasibility for production of metal matrix composites by introducing SiC powders to AA 2024 chips. This allowed for detection of a helical material flow forming the wire and the detrimental effects of excessive SiC reinforcements: crack-opening and inhomogeneous mechanical properties as a result of conglomerate formation. This finding might be representative for the potential challenge when processing machining waste, due to the high risk of contamination and increased amount of oxides present as a result of the high surface to volume ratio.

The comparative approach presented in this work aims at identifying processing characteristics, by applying FEP to chips and bulk material while keeping all controllable parameters identical. Despite the applied conditions not leading to optimized extrudate properties, they assist in understanding the development of thermal and strain conditions during FEP for different feedstock conditions.

Experimental Methods

Material. The base material for the extrusions is cast aluminum with 10 wt.% copper. This binary alloy is chosen to avoid more complex microstructural processes, i.e. phase transformations in multi-phase regions, as typical for commercially relevant alloys [10], potentially affecting the processing behavior. The raw material was produced by chill casting using graphite coquilles and controlled solidification from the melt by lowering them into a water bath. The bulk feedstock for FEP was machined from the cast block and after removing the cast skin, uniform chips were collected without the use of coolant or lubricants, see Fig. 2a). The billet is used without further heat treatment, while the chips are being tapped and compressed in multiple steps in the container with a final compaction force of 100 kN before FEP. The dimensions of the material in the container before and after processing are given in Table 1. The non-extruded feedstock left in the container after FEP is denoted as residual (feedstock) material.

Table 1: Dimensions of feedstock material at 100 kN static loading, before and after FEP as well as of the extruded wires.

	Diameter [mm] x Length [mm]		
	Feedstock before FEP	Residual material	Extruded wire
Bulk, 10 mm	49.8 x 50.0	50.0 x 19.6	9.90 x 762
Chips, 10 mm	50.0 x 41.9	50.0 x 19.0	9.95 x 120
Chips, 7 mm	50.0 x 41.1	50.0 x 19.8	6.95 x 208

Friction Extrusion Processing. For processing the Al-Cu feedstock, the dedicated friction extrusion machine FE100 (Bond Technologies, IN, USA) was used. It utilizes a rotating container from 42CrMo4 steel with 50 mm inner diameter and hydraulically driven flat faced dies from X40CrMoV5-1 steel with a central orifice of 7 and 10 mm diameter and a land length of 8 mm, resulting in extrusion ratios of 51 and 25, respectively. For all processes, the temperature is recorded with a K-type thermocouple installed in the die at a radius of 16.5 mm, at a distance of 1 mm from the die face.

The extrusions are performed force-controlled at 150 kN while keeping container and feedstock at a constant rotational speed of 150 rpm. Before applying these extrusion process parameters, a program step with limited force (50 kN) and higher rotational speed (300 rpm) is used to ensure defined contact and to initiate frictional heat generation without inducing extreme torque peaks. The transition from this pre-heating step to the target parameters via a 10 s ramp is started after a die movement of 1 mm.

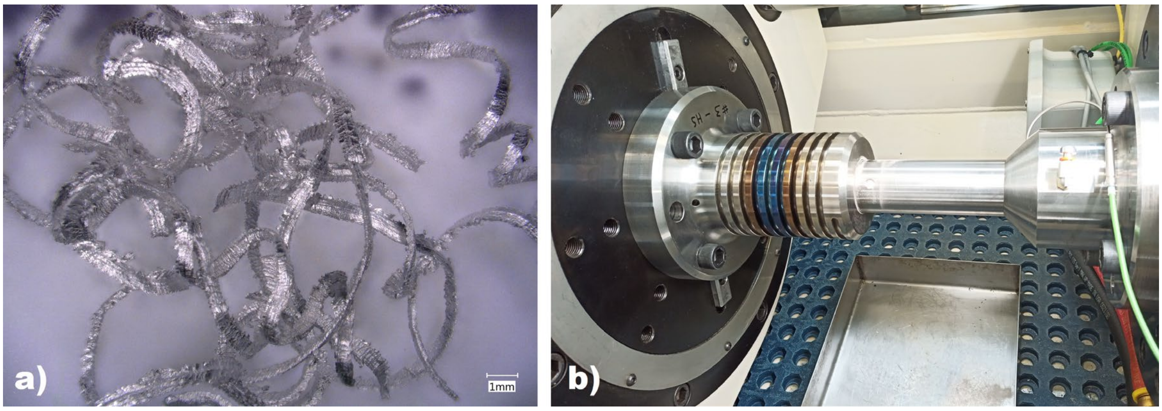

Fig. 2: a) AlCu10 chips used as feedstock and b) tool setup in the FE100 with the rotating container on the left and the die, mounted to a die holder, advancing from the right.

Table 2: Density of feedstock during preparation and processing of AlCu10 chips.

	Density [g/cm³]	
	7 mm wire extrusion	10 mm wire extrusion
as-cast material	2.87	2.87
tapped machined chips	0.22	0.21
pressed (60 kN, static)	1.52	1.49
pressed (100 kN, static)	1.63	1.59
extruded (150 kN, 150 rpm)	2.81	2.79

For bulk extrusion, a billet of 50 mm length and a weight of 277 g is used. Due to the low tapped density, the chips are compacted first in the container at 60 kN in a hydraulic press and the resulting feedstock of 132 g is further compressed at 100 kN after installation of the container in the FE100, see setup in Fig. 2b).

The change in feedstock density during the compaction is given in Table 2. The extrusion of the AlCu10 chips is then started without preceding friction consolidation phase. In all processes, the feedstock is secured against rotation towards the container by mechanical interlocking with the container bottom via protruding set screws.

Analysis. The evaluation of processing characteristics is based on the machine readings, with extrusion force and spindle rotation as control parameters and die plunge speed, temperature and spindle torque as machine response. Microstructure analysis on sections of the extruded wires was performed with a VHX-6000 digital microscope (Keyence, Germany). The analyzed samples are prepared by grinding up to 4000# SiC-foil, polishing with 1 µm diamond-suspension and electrolytical etching with Barker-solution (90 s, 15 V). Wires in cross- and longitudinal sections are prepared as well as longitudinal sections of the transition zones, covering the residual feedstock material and the extruded wires.

Results and Discussion

Processing Behavior. While billet and chips were subjected to the same processing parameters during FEP, the machine response, i.e. temperature, extrusion speed and spindle torque, shows significant differences. For the bulk extrusion of 10 mm wires, Fig. 3a), the die contact was made after 15 s at 50 kN and 300 rpm. After 20 s the targeted extrusion parameters of 150 kN and 150 rpm were applied over a 10 s ramp. For die temperature and spindle torque an asymptotic stabilizing during FEP was observed with a final temperature of 544°C at a die advance rate of 3 mm/min or an extrusion speed of 1.25 mm/s, respectively.

The initial period in the FEP from chips, Fig. 3b), is characterized by a strong effect of compacting the feedstock. Due to the displacement limit for the pre-heating, the ramp to target extrusion parameters was applied after 7 s. With the increase in extrusion force to 150 kN, the die advanced rapidly and the targeted extrusion force was built up with a certain delay. After around 40 s, the process stabilized with slowly decreasing spindle torque and an ongoing increase in temperature at the die, ultimately reaching 497°C at a die advance rate of 7.5 mm/min. Neglecting the fact that consolidation of the chips took place simultaneously, this yields a theoretical extrusion speed of 3.1 mm/s. It should be noted that the applied rotation allowed for much higher compaction, even at lower forces than during the previous static compression at 100 kN. Despite extruding from chips at initially low temperatures, no spilling of chips was observed during processing.

Comparing both extrusions at the same temperature level of around 495°C, the extrusion from chips shows a 35 % higher die advance rate, which indicates a lower extrusion resistance. For a further interpretation, also the residual void volume, still present in the feedstock during FEP, needs to be considered, see Fig. 5b).

The degree of consolidation between the different processing steps is compared to the cast material by measuring the density, given in Table 2, according to sample weight and volume. The compacted chips before FEP presented around 44 % void volume. Around 97.9 and 97.2 % density could be achieved in the FEP from chips for 7 and 10 mm wire diameter, respectively. The lower density in comparison to the wire from cast material is caused by volumetric defects present in the wires extruded from chips, see Fig. 6.

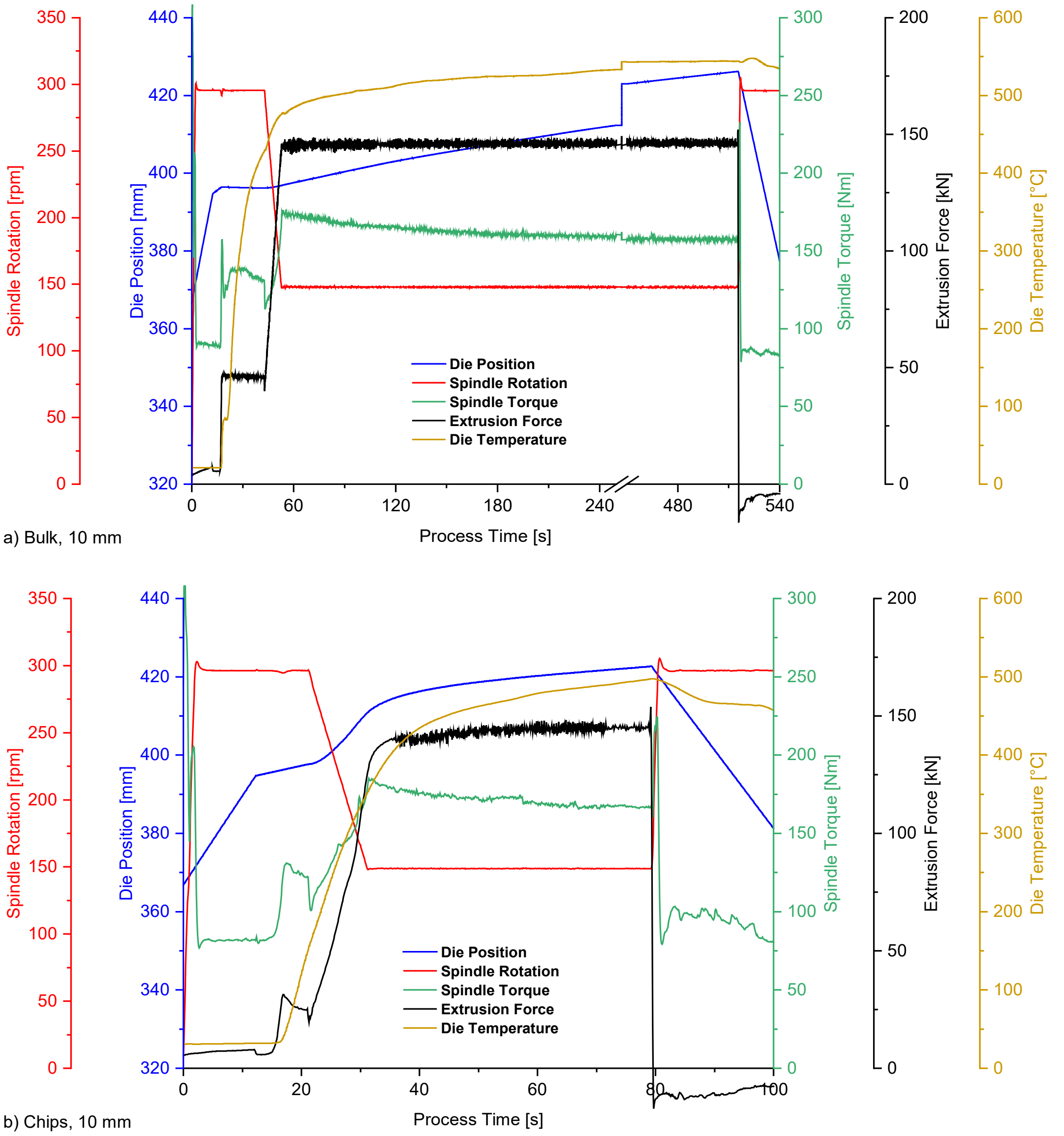

Fig. 3: Process plots for FEP of 10 mm wires from a) bulk and b) chips material of AlCu10. The target parameters of 150 kN extrusion force and 150 rpm relative rotation are applied after the pre-heating phase in the time from 53-516 s (bulk) and 31-80 s (chips), followed by the die retraction.

When comparing the performed extrusions from bulk and chips, the die advance rate and temperature evolution during processing are of particular interest. As shown in Fig. 4, the die advance rate correlates with the feedstock type. Potential for compaction, as given for chips, results in high initial die advance rates. The similarity in die advance rate between the 7 and 10 mm wire extrusions indicates that initially most of the die movement contributes to consolidation, whereas at a later stage during FEP, the slight divergence in die advance rates can be attributed to the different extrusion conditions induced by the chosen extrusion ratios. For the bulk material feedstock, the extrusion speed decreases slightly over processing time, as opposed to the temperature. The temperature evolution at the die face during FEP shows great similarity for both feedstock conditions for 10 mm wire extrusion, despite the difference in pre-heating. The torque during initial contact shows similar increase and peak values as well.

Considering the different resulting extrusion rates, the reduced heat conductivity in a feedstock with high void volume and the altered shear strain response to torque loads, allows for the seen similarity to conclude that local friction and shear introduction conditions determine the temperature evolution and might be comparable for both bulk and chips feedstock. For the 7 mm wire extruded from chips, a slightly lower temperature at the die was observed.

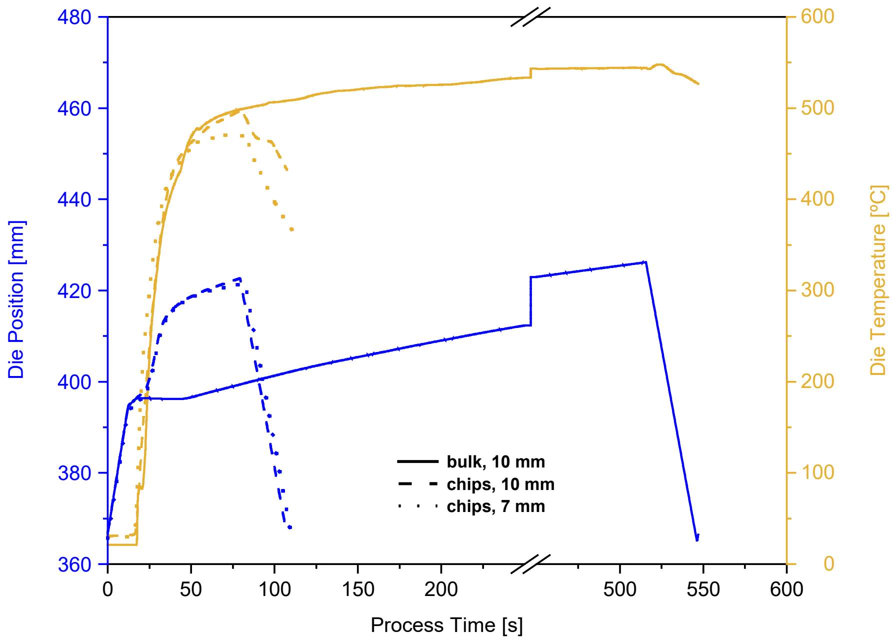

Fig. 4: Comparison of die position and die temperature over processing time for FEP of 10 mm wires from bulk as well as 7 and 10 mm wires from chips of cast AlCu10.

Extrudate Properties. Metallographic examination revealed the induced microstructural changes. In Fig. 5a), the material flow towards the die orifice is shown for bulk extrusion. The billet material is affected up to a depth of 5 mm from the die face at the circumference to around 15 mm at the center. While the deformation of the grain structure is clearly visible, no significant refinement, homogenization or rotational deformation can be observed after the prolonged application of the extrusion parameters, see Fig. 5a), as opposed to the initially extruded parts of the wire, see Fig. 6. The residual feedstock from chips is shown in Fig. 5b) and illustrates deformation throughout the full depth of feedstock material in the container, due to the high initial void volume. Furthermore, a pronounced crack in a half circular pattern is visible at a depth of around 9 mm from the die face, reaching up to the circumference of the die contact area, as marked in Fig. 5b). Above this crack, individual chips can still be detected while showing significant elongation in direction of the material flow through the die orifice. Below the crack, irregular porosity between chips can be seen. The structure of the chips is only broken up at the contact zone to the die, leading to a well grain-refined outer layer in the extruded wire.

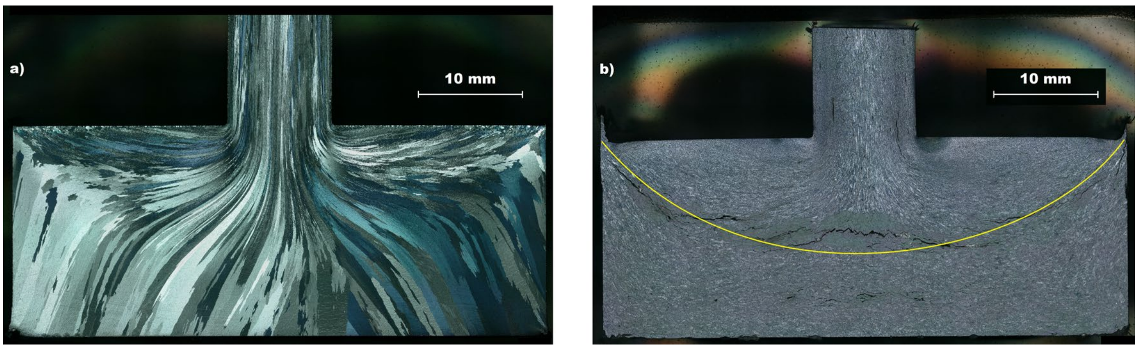

Fig. 5: Transition zone from feedstock to wire for 10 mm extrusions from a) bulk and b) chips of AlCu10 processed at 150 kN, 150 rpm. The transition zone represents the processing conditions after extrusion of 762 mm (bulk) and 120 mm (chips) of wire.

When analyzing the first 35 mm extruded wire, see Fig. 6, the mentioned refined outer zones are more pronounced. While a higher fraction of refined material in the wire is present at the beginning of FEP, the grain size in these outer areas shows no significant change throughout the process. The decrease in refinement can be observed by comparing the resulting wire microstructures at the initial, Fig. 6, and final stage, Fig. 5, of the process. For 10 mm wire extrusion from chips feedstock the width of the grain-refined and visibly pore free outer layer decreases from 3.0 mm at 35 mm wire length to less than 0.9 mm at 120 mm. For bulk feedstock the longer process time leads to a more prominent indication, reducing the width of the refined outer layer from 1.5 mm at 35 mm wire length to less than 0.1 mm after extrusion of 762 mm.

Combined with the measured temperature evolution, this supports the hypothesis that for both extrusions from bulk and chips, the extrusion resistance is not solely determined by processing temperature but rather by the efficiency of shear introduction, as indicated by the amount of refined or homogenized material in the wires. The reduced or finer dispersed porosity in the 7 mm wires extruded from chips as well as the larger amount of refined grains, see Fig. 6, correlate with higher pressure and strain as a result of the increased extrusion ratio, while obtaining a similar die advance rate. The lower recorded extrusion temperature might further add to increased shearing and subsequent grain refinement in the material.

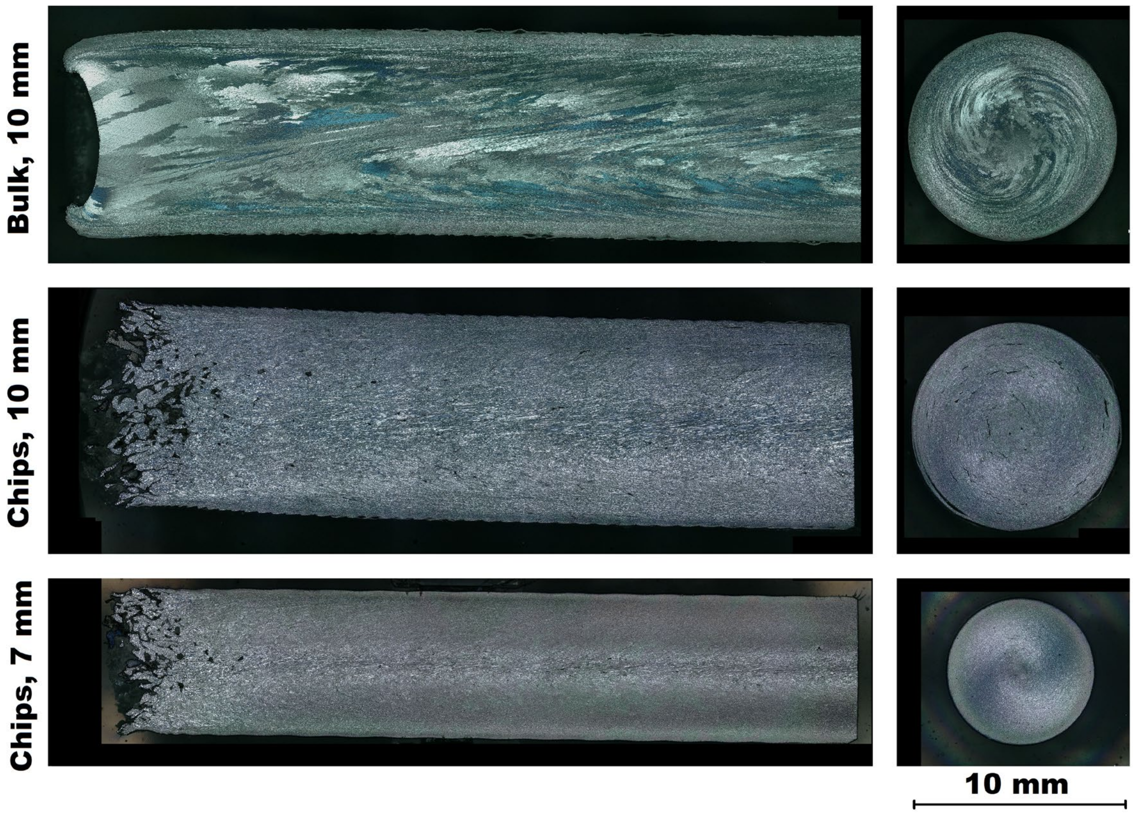

Fig. 6: Microstructure overview of the wires extruded at 150 kN, 150 rpm from bulk and chips AlCu10 feedstock: longitudinal sections of the first 35 mm of extruded wires (left) and cross-section after 50 mm of extruded length (right).

The general trend of decreased shearing and refinement with process time and increasing temperature is an effect well investigated by Li et al. [11, 12] via the introduction of marker material in the feedstock. In the current study, this behavior is supported by the described decrease in refined material in the outer areas of the extruded wires for 10 mm extrusions from both bulk and chips feedstock. The changes in refinement and temperature over the process duration affect the FEP, regardless of feedstock material. This can be partially related to the force-controlled process, resulting in an extrusion rate dependent on the extrusion resistance of the processed material.

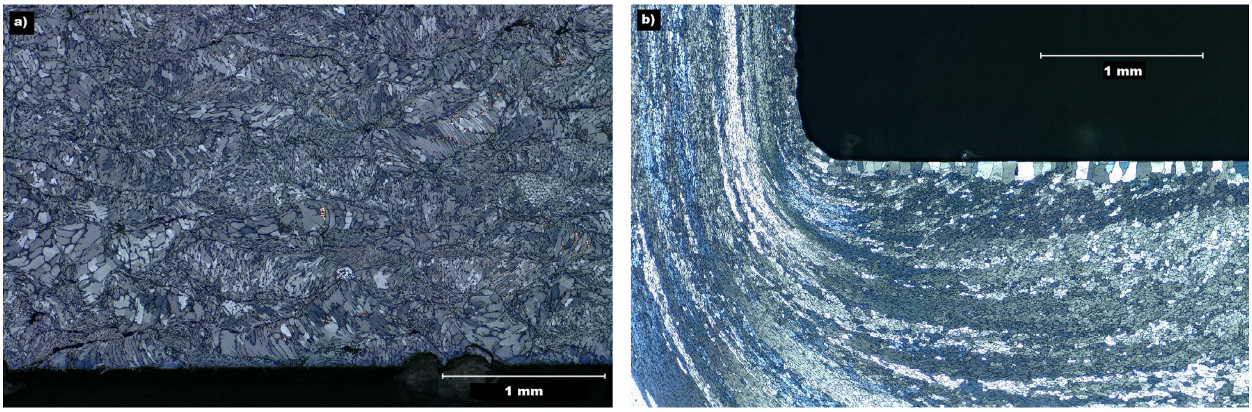

Fig. 7: Microstructure after FEP in a) the AlCu10 chips feedstock at the bottom of the container and b) material flow in bulk extrusion at the die face and orifice.

A benefit of extrusion from chips is the already high level of homogenization compared to as-cast material. The consolidated chips structure, see Fig. 7a), is characterized by what appears to be dendritic θ-phase structures as a consequence of the high Cu-content in the AlCu10 alloy used [10]. As a result of insufficient strain conditions for refinement, the initial microstructure of the chips as well as the presence of boundaries between individual chips are observed in the resulting wires throughout the full extrusion length. In the outer areas of the extruded wire, comparable to the bulk extrusion, a higher degree of grain refinement is observed. While similarly small grains up to 10 µm are present in these refined areas, a notable amount of significantly larger grains (> 100 µm) is observed. A potential reason is the lower local strain as a consequence of the lower shear resistance in the compacted chips feedstock when compared to extrusion from bulk feedstock.

For FEP from bulk material feedstock, a strong deformation of the cast structure is seen in the proximity of the die face, resulting in a grain size of 10-15 µm in the areas with shear introduction from the relative rotation between die and feedstock. Fig. 7b) shows larger grains in the contact zone with the die face, a possible result of temperature-induced grain growth, following pronounced grain refinement by dynamic recrystallization during FEP.

Conclusions

In the presented study, a direct comparison of FEP from AlCu10 was performed for feedstock material in bulk and chips under identical process parameters. The chosen parameters proved sufficient for generating mechanically sound extrudates. Differences in processing behavior and microstructural evolution are observed and discussed with the main findings summarized as follows:

- Simultaneous friction extrusion and consolidation of chips has a significant dampening effect on the establishing of pressure conditions in front of the die, as seen from the die advance rate and axial force. The effect of consolidation on the die advance rate reduces after application of the actual extrusion parameters and stabilizes in line with the temperature.

- Highly similar heating rates, recorded for both bulk and chips feedstock, indicate that for the given process parameters, friction and shear conditions at the immediate die-feedstock interface control the thermal evolution. This is further supported by the similarity in torque during application of extrusion parameters.

- The volume of refined grains observed in the extrudates decreases over time, indicating a detrimental effect of increasing process temperature for both bulk and chips feedstock.

Regarding the relatively low volume of refined grains during FEP from bulk, it is suggested to increase extrusion force or to reduce spindle rotation to induce more efficient shear introduction and thus grain refinement. For chips extrusion, a similar approach can be beneficial, as the higher extrusion ratio of 51, as opposed to 25, provided significantly better homogenization and refinement, indicating the need for higher pressure or strain rates during FEP.

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Data Availability

The data related to this research is available online (https://doi.org/10.5281/zenodo.5910334).

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