Property grading by friction induced and continuous solid-state recycling of aluminium scrap

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Abstract. Saving energy and reducing emissions in all sectors is essential if the ambitious climate targets of various European countries are to be met. One way of achieving this is to recycle metallic materials, which require a lot of energy to produce, in a way that minimizes the use of energy and resources. The friction-induced solid-state recycling process enables the energy-efficient recycling of what is in theory an endless aluminium semi-finished product through the continuous rotation of the wheel used. The past investigations proved the energy-efficient recycling of new aluminium scrap (powder, foil, chips) to a full semi-finished product with good properties. The continuous character of the process along with the likewise continuous feeding of the material to be recycled enables both mixing and successive processing of different aluminium alloys. For this purpose, the processed four different aluminium alloys are selectively mixed and processed simultaneously, as well as different alloys are processed one after the other to achieve a gradation of properties along the length of the semi-finished product. The recycled semi-finished product is examined regarding die filling, hardness, tensile strength as well as microstructure. The central result of the investigations is the fact that the friction-induced recycling process has different possibilities for grading the properties and microstructure in a wide range.

Introduction

Reducing greenhouse emissions is essential to limit global warming. In many parts of the world, political guidelines are being developed and implemented. In order for Germany to meet its climate targets by 2030, measures must be implemented in many areas of industry, transport, trade and housing [1].

If the emissions of complex systems and assemblies are analysed in the context of engineering, both the emissions generated during production and during use must be considered. For example, the production emissions for a car with a petrol or diesel engine account for 15-20% of total emissions. For a fully electric car, assuming a green electricity mix, up to 95% of the total emissions are those from production [2].

In order to reduce emissions during the production of complex systems, it makes sense to change the production of semi-finished products. In theory, metals such as aluminium can be recycled an infinite number of times [3]. The advantage of recycled materials is that the energy required for recycling is significantly lower than for primary production. Only 10% of the energy required for the primary production of aluminium is needed to recycle aluminium. Recycled aluminium therefore has a significantly lower energy balance of 17.7 MJ/kg [4]. This means that the production of aluminium using recycling processes has great potential for savings compared to primary production [5]. Research in recent years has shown that in addition to the conventional recycling of aluminium, in which the aluminium has to be melted down and toxic slag is produced, solid-state processes are very suitable for recycling [6].

Some studies have shown that it is possible to produce semi-finished products from aluminium waste using a conventional extrusion line. To enable processing on a conventional system, the aluminium waste is first compacted in a hydraulic press. They are then extruded into a semi-finished product using large plastic deformations in an extrusion line. Profiles can be produced that have similar or better properties than conventionally recycled aluminium. The reason for this is that the aluminium oxides are broken up by the plastic deformation, dispersed in the semi-finished product and serve as reinforcement [7]. It has also been shown that an ECAP mould improves the mechanical properties and electrical conductivity of the extruded semi-finished products because it ensures higher pressures and higher strains [8, 9].

To reduce the heat input from the outside, the extrusion process can be carried out with a rotating die. This process is known as friction extrusion. Frictional heat is generated by constant axial pressure and the rotation of the die, which heats the chips in the billet chamber. This plasticises them and they flow through the hole in the die. The process has good energy efficiency because no external heat needs to be supplied to plasticise the aluminium [10].

Both processes presented have a discontinuous process flow. An approach to the continuous recycling of chips is being researched using the Conform process. In those research titanium chips are processed in a conventional conform plant. The results show good ductility and strength of the extruded wire. The surfaces, on the other hand, show poor quality. Additionally, the mould could not be filled, and the resulting cross-section is therefore not ideally round [11].

In addition to the explained current research to reduce emissions during production, it is also possible to cut emissions during the utilisation phase of a product. For example, in order to reduce vehicle emissions during the use phase, steel materials are increasingly being replaced by aluminium or magnesium. These have a low density and some, such as EN AW-7075, have strengths comparable to those of steel [12]. By substituting materials, up to 10 % of CO2 emissions per kilometre can be saved during use [13]. In addition to the substitution of materials, it is important that the components of the vehicle are designed to be load-adapted. This avoids unnecessary material accumulation and further reduces weight. There are two ways of doing this. On the one hand, a component can be locally reinforced with a higher-strength material such as carbon fibre [14] or the strength of the material can be increased. This can be achieved, for example, by partially changing the properties of the material [15]. As a result, localised load peaks can be absorbed by the high-strength area. On the other hand, a higher material thickness can be set locally. This results in a localised reduction in stresses due to the larger cross-sectional area. As a result, a weight reduction of up to 20 % is possible [16].

The investigations carried out here show how an energy-efficient, continuous recycling process for aluminium chips enables the production of load-adapted semi-finished products. Therefore, it offers the possibility to reduce emissions during the production and the use phase of the later product. The process has been developed at the Chair of Forming and Machining Technology, Paderborn University. The experimental setup works according to the principles of the Conform process. The advantage of the innovative process is the continuous processing of raw materials like chips. In theory, unlimited lengths of semi-finished products can be produced. Furthermore, the process does not require an external heat source, but works with frictional heat and thus is very energy-efficient. As a result, a self-regulating stationary state of the process is achieved after a short time, in which the temperature, torque and mass flow of the supplied chips are kept constant. The central point of this research is how the mixing of different aluminium alloys affects the process and the semi-finished product produced. The reason for this is that chips in an industrial environment are rarely ideally separated, but often consist of a mixture of different alloys. Furthermore, two materials can also be deliberately mixed in order to adjust the chemical, physical or mechanical properties of the semi-finished product. This allows local areas with higher strengths to be produced and components with load-optimised properties to be manufactured.

Methods and Materials

The set-up used for the tests is shown in Figure 1. At its centre, the process consists of a wheel, a tool insert and a tool holder. The wheel is driven by a motor during the process. In addition, a gearbox is installed between the two components to enable the high torques. For all investigations carried out for this paper, the speed was set at n = 11 rpm. During the entire process, the aluminium chips are filled into the designated groove of the wheel via a funnel. The groove has a width w = 7 mm and a depth t = 6 mm. The cross-sectional area available for the chips is continuously reduced by the tool insert to compress the chips. As a result, the air between the chips is pressed out of the groove. As a result, the density, which initially varies between ρ = 0.24 g/cm³ - 0.35 g/cm³ depending on the chip shape, increases to 2.7 g/cm³. In addition to the compression of the chips, the relative movement between the wheel and the aluminium residues leads to friction. Due to the friction, the process itself generates the necessary heat to plasticise the chips. High pressures are generated between the wheel and the tool insert during the process, which cause the oxide layers of the aluminium to break open in the last third of the forming zone and thus weld the chips together. At the end of the tool insert there is a counterholder that deflects the material and ensures additional forming of the aluminium. This breaks up the remaining oxide layers and a homogeneous semi-finished product is extruded. The extruded wire in the tests presented here has a diameter of d = 5 mm.

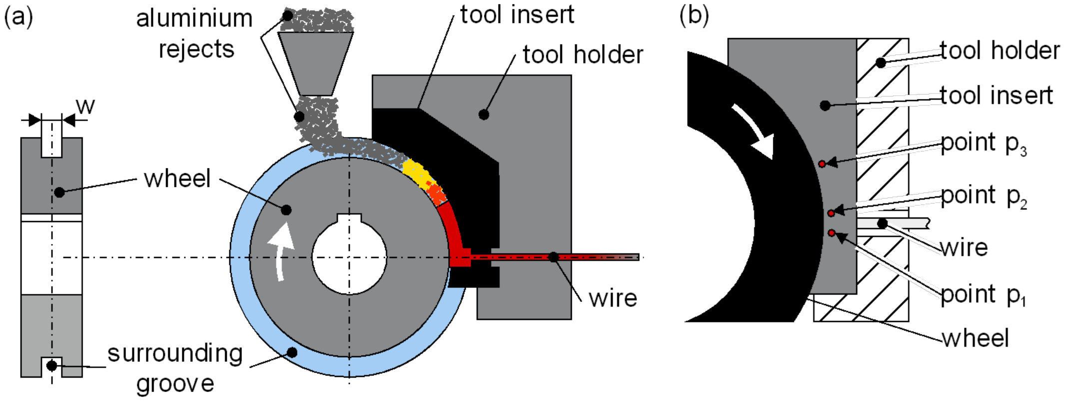

Figure 1: Set-up of the friction induced recycling process with a) all components required for extrusion and b) a close-up of the extrusion zone and the temperature measuring points [17]

Chips of two wrought alloys and one cast alloy are used for the experimental investigations. Defined ratios of the alloys EN AW-6060, EN AW-7075 and EN AC-43000 are mixed and then fed into the process. In each case, two of the alloys are mixed together in different mass ratios. The mixture alloys analysed are listed in Table 1.

Table 1: List of the mixtures produced from the various aluminium alloys

Alloys and mixing ratio
50% EN AW-6060 50% EN AW-7075
50% EN AW-6060 50% EN AC-43000
75% EN AW-6060 25% EN AW-7075
75% EN AW-6060 25% EN AC-43000

As aluminium chips are used in the investigations, the characteristic features of the individual chip shapes of the different alloys are shown in Table 2. The ratio of volume to surface area is relevant for processing, as this ratio allows conclusions to be drawn about the volume proportion of aluminium oxide in the entire chip. An increasing oxide content reduces the ductility of the semi-finished product produced.

Table 2: Characteristic properties of the aluminium chips used

Alloy **Characteristic**	**EN AW-6060**	**EN AW-7075**	**EN AC-43000**
Chip length[mm]	2.1 ± 0.26	1.7 ± 0.1	1.8 ± 0.06
Chip width [mm]	1.8 ± 0.12	1.1 ± 0.1	1.5 ± 0.13
Chip thickness [mm]	0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0.01
Bulk density [g/cm³]	0,29 ± 0.01	0.24 ± 0.01	0.34 ± 0.01

To analyse the mixtures, the stationary process temperature is recorded during the experiment and differences between the alloys and their mixtures are discussed. In addition, the hardness, tensile strength and uniform elongation of the semi-finished products produced are analysed. The hardness measurement is carried out using the Vickers method with an indentation force of N = 2.942 N (HV0.3). A hardness measurement is carried out at a total of thirteen points in the wire cross-section. The distribution of the points can be seen in Figure 2.

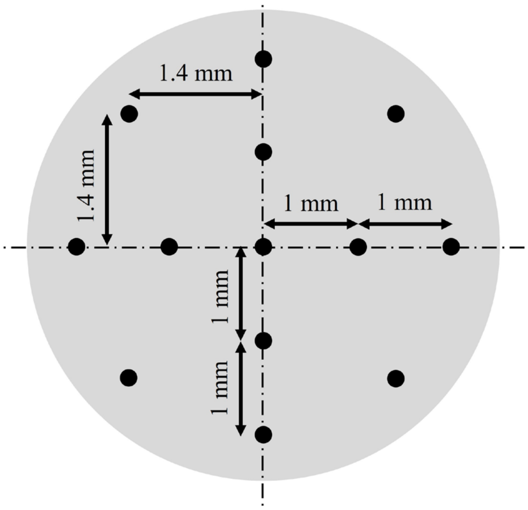

Figure 2: Position of the thirteen hardness measuring points on the cross-section of the extruded semi-finished product

Results and discussion

As the alloys used have different mechanical properties, an effect on the temperature is to be expected. Table 3 lists the steady-state process temperatures of the friction-induced recycling process for the alloys and their mixtures analysed. As the alloys EN AW-7075 and EN AC-43000 have higher strengths compared to EN AW-6060, the steady-state process temperature for these two alloys is higher. The reason for this is that the flow stress required for the process is only achieved at higher temperatures.

If the EN AW-6060 (75 %) alloy is mixed with the EN AW-7075 (25 %) alloy, a steady-state final temperature of $T_S \approx 350$ °C is achieved with a low mass fraction of EN AW-7075 (25 %). This lies between the steady-state end temperatures of the two pure alloys

($T_{S,EN\ AW-6060} \approx 310$ °C, $T_{S,EN\ AW-7075} \approx 410$ °C). If the proportion of EN AW-7075 is increased to $n_L = 50$ %, the steady-state final temperature rises to $T_S \approx 410$ °C. This corresponds to the steady-state process temperature of the pure alloy EN AW-7075. A similar phenomenon can be observed if the alloy EN AW-6060 (50 %) is mixed with EN AC-43000 (50 %). Then the steady-state final temperature of $T_S \approx 390$°C also corresponds to that of the cast alloy EN AC-43000.

Thus, the steady-state processing temperature during the process does not scale linearly with the mass fraction of the alloys. If a certain limiting quantity of the higher-strength alloy is mixed (approximately 50 %), the process temperature rises to that of the higher-strength alloy. From this it can be concluded that this is the dominant alloy in terms of the process temperature at a higher mass fraction.

Table 3: Stationary process temperatures of the analysed alloys and their mixtures

Alloy / alloy mixture	**Stationary process temperature**
50% EN AW-6060 / 50% EN AW-7075	~ 410 °C
50% EN AW-6060 / 50% EN AC-43000	~ 390 °C
75% EN AW-6060 / 25% EN AW-7075	~ 350 °C
75% EN AW-6060 / 25% EN AC-43000	~ 340 °C
EN AW-6060	~ 310 °C
EN AW-7075	~ 410 °C
EN AC-43000	~ 390 °C

Figure 3 compares the mechanical hardness of the profiles produced from the chips of different alloys with the hardness of the profiles produced from pure alloys from the friction-induced recycling process. The figure shows the mean values from three measurements. The hardness points are measured on the cross-section of the profile according to the procedure described. In addition to the measured values from the experiment, a calculation of the theoretically expected hardness values is also shown. The calculations are carried out to check whether the mechanical properties of two or more alloys can be predicted using a simple method. For the calculation, the respective proportion of the different alloys is multiplied by the mechanical characteristic value (in this case the hardness) of the pure alloy. The corresponding values are then added together. To determine the mechanical properties, the alloys used were processed in their pure state in the friction-induced recycling process and the parameters were determined. The hardness values also show that the characteristic values of EN AW-7075 dominate in a mixture of EN AW-7075 (50 %) and EN AW-6060 (50 %). At $H = 98.9$ HV0.3, the profile produced shows only a slight difference to the hardness of the base alloy of $H = 103$ HV0.3. If the calculated value is considered for this test point, it is noticeable that it is significantly lower at $H = 73.5$ HV0.3. For all other mixtures, however, the calculated values deviate only slightly from the hardness values determined in the experimental test.

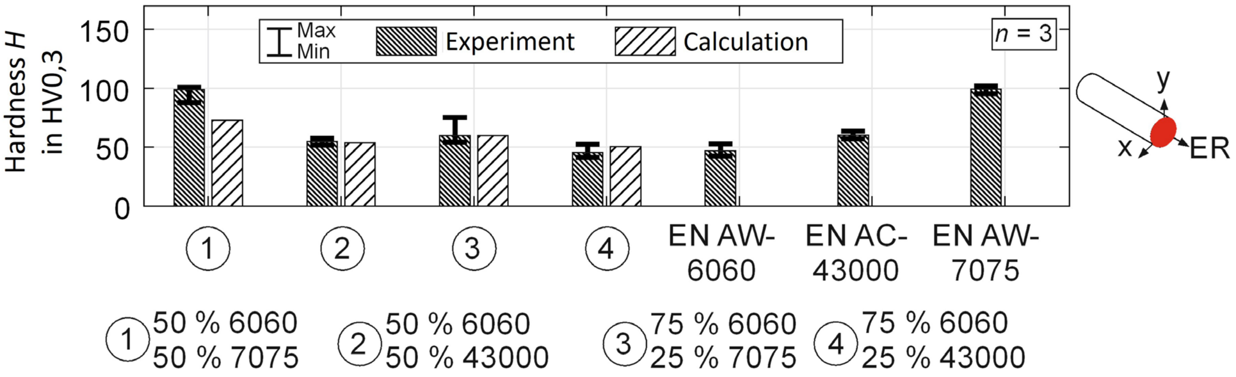

Figure 3: Hardness of the different alloys and mixtures investigated

In addition to the mechanical hardness, the recycled wires were subjected to tensile testing in form F in accordance with DIN 50125. The results, shown in Figure 4, are the respective mean values from at least three samples for each test point. The tensile strengths achieved for the alloy mixtures are almost identical to the calculated values. Nevertheless, the mean values of the experimental tests are slightly higher than the calculated values for all mixtures. If, for example, the tensile strength to be expected for a mixture of EN AW-6060 (75 %) and EN AW-7075 (25 %) is calculated based on the previously determined tensile strengths of the pure alloys, a strength of R_m = 185 MPa is anticipated. The investigation resulted in an average strength value of R_m = 207.4 MPa. This represents a deviation of 12 % from the calculated value. Deviations of 10 – 15 % are also found for the other mixtures.

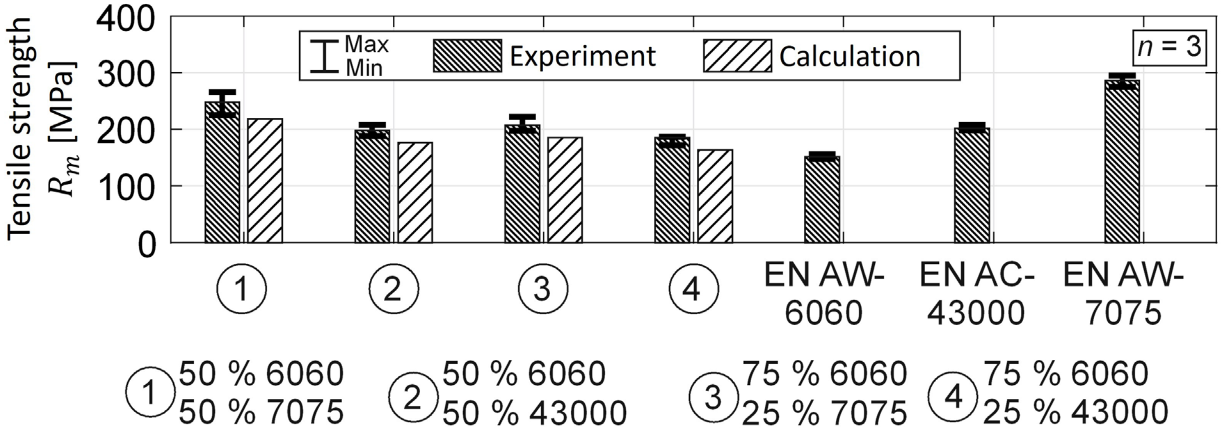

Figure 4: Achieved tensile strengths of the different alloys and mixtures

The results for the uniform elongation are shown in Figure 5. It is evident that the calculated results deviate from the measured results. The deviation for a mixture of EN AW-6060 (75 %) and EN AC-43000 (25 %) is a particularly noticeable difference. A uniform elongation of A_g = 22.2 % was measured in the experimental test. The elongation is therefore around 93 % greater than the calculated result (A_g = 11.5 %). For the other test points, the measured uniform elongation is below the calculated values.

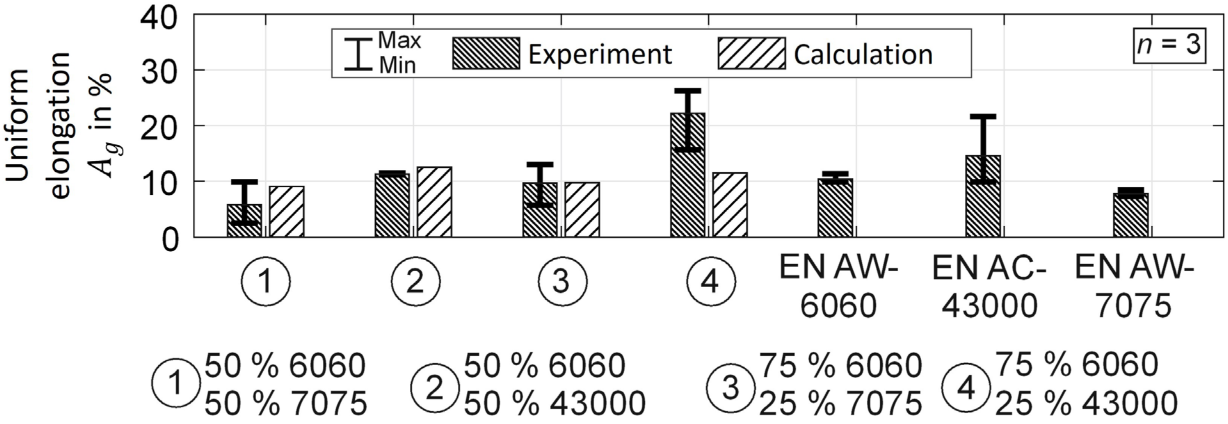

Figure 5: Achieved uniform elongations of the pure alloys and mixtures

In addition to an influence on the mechanical properties, the microstructure is also influenced by mixing different aluminium alloys. Figure 6 shows the microstructure of a mixture of EN AW-6060 (75 %) and the proportions of the cast alloy EN AC-43000 (25 %) shown with a green frame. As the mass fraction of the wrought alloy is significantly higher, the microstructure of the casting alloy can only be recognised as embedded stripes in the mixture. Due to the compaction, extrusion and plasticisation of the material, it is heavily deformed and the width of the stripes deviates significantly from the chip thickness of the EN AC-43000 chips used (d_S = 0.1 mm). The fact that the grain structures of the different alloys can be easily distinguished from each other makes it possible to draw conclusions about the process. In future investigations, the alloy content can be specifically adjusted to investigate the material flow during the process in more detail. In addition, the deformation acting on the aluminium chips can be approximated.

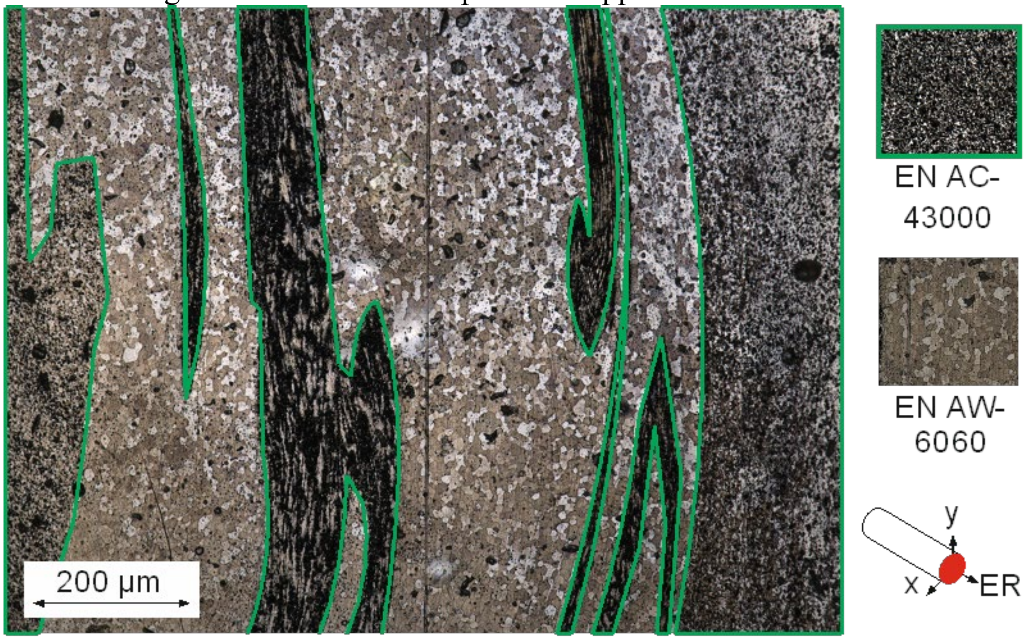

Figure 6: Microstructure of an alloy mixture of 75 % EN AW-6060 and 25 % EN AC-43000

Summary

This paper briefly introduces the friction-induced recycling of aluminium chips and explains the process. This is a solid-state process and does not require an external heat source. The process is also characterised by the fact that it runs continuously, and no interruptions are necessary. In the friction-induced recycling process presented, defined mixture ratios of three aluminium alloys were processed. The experimental investigations proved that it is possible to adjust the properties of the extruded semi-finished product. For example, the addition of EN AW-7075 to an EN AW-6060 leads to a significant increase in strength. In addition, the achievable tensile strength and hardness can be predicted using a simple mathematical model. By mixing two alloys, the properties can be changed locally using the process presented. It is also possible to process the alloys one after the other without interrupting the process. This means, for example, that components can be produced from EN AW-6060 and locally reinforced with EN AW-7075. As a result, the semi-finished product can be manufactured to suit the load during its use phase and the components made from it are lighter and lead to lower emissions during use.

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