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Effect of Joining Mechanism on the Mechanical Recycling of Polymer–Metal Composite Parts

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Abstract: In order to be able to recycle composite components made of polymer and metal, which are used in the automotive industry, the joints must be broken. The success of the separation is influenced by the stress and also by the joining mechanism between the polymer and the metal. Here, force-fit and form-fit connected components are produced and crushed in a rotor impact mill with two different rotors. The results show that the crushing results differ significantly for the different rotors and for the various joining processes. In short, the hammer-type rotor provides much finer and better-separated fragments and the force-fit joints enable a better separation of metal and polymers. The additional cooling of the samples also changes the result in a way, where deep cooling significantly improves the separation of the metal and the polymer. Different types of polymers also led to a different separation result with both rotors.

Keywords: crushing; recycling; plastic; hammer mill

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1. Introduction

The recycling of batteries receives significant attention, looking at the high-cost materials in the black mass. However, around the battery are many components made of polymers and metal, such as different high voltage connectors. Joining two different materials to form a component can have several advantages, i.e., weight can be saved, plus, the various advantages of different materials can be specifically utilized to make the component safe. In the battery sector, where components transport high currents, polymers are used for insulation because they have hardly any electrical conductivity as metals. Another advantage of polymer–metal composites is the greater freedom of design, as polymers can be molded into any shape in large quantities without having to be reworked. Their properties also qualify them to be used in combination with metal to build high-strength structures. This means, for example, that polymer stiffening ribs can be incorporated into a basic metal structure. The stiffness has been increased significantly, but the weight only minimally [1].

There are various manufacturing processes for joining polymer to metal. The most frequently used methods include mechanical joining such as plug-in connections or adhesive bonding. However, several process steps are usually required for plug-in connections, while curing times and the use of chemicals must be taken into account for adhesive bonding. Another option is friction stir spot welding, to achieve high strength, or the friction-based injection clinching joining technique. In aviation, the direct assembly of polymer onto the pretreated metal part, for example in an autoclave, is frequently used. Metal insert injection over-molding is a process that has many advantages and was also used to manufacture the components in this work. It is based on the injection molding process for polymers; the metal insert is placed into the mold and encased in polymer. Mechanical interlocking mainly creates the connection. The process is cost-effective, fast and can be used for complex geometries. In order to strengthen the connection, form-fit connectors or surface structuring can be applied on the metal insert [2,3]. Within the selected manufacturing process, further distinctions can be made with regard to the joining mechanism. According to DIN 8593 [4], a distinction is made between nine different variants, whereby, in this work, all joints are produced by primary forming. The respective joining mechanisms can also be divided into three groups, the basic principles of a joint: the force-fit, the form-fit and the material-fit connections. The joining principle prevents the joint from loosening in various ways. In the case of form-fit joints, the geometry of one or both joining partners prevents the joint from loosening. In a force-fit joint, the components are joined in such a way that a frictional force is created between the joining partners. If this frictional force is greater than the engaging force, the joint is prevented from loosening. In the case of a material-fit connection, for example, an additional bonding agent is used to create a chemical bond between the joining partners, which prevents the bound from loosening due to adhesion and cohesion mechanisms. Materially bonded joints are usually non-detachable joints. With form-fit and force-fit joints there is the possibility of a detachable joint so that the joining partners do not have to be destroyed if the joint is to be cancelled [5].

In order to recycle these composites, the joints must be broken in order to separate the materials from each other by type [6]. This is the most challenging in the case of material-fit connections, as the chemical bonds between the materials must be broken. Mechanical recycling processes are only suitable to a limited extend here, which is why the focus of this work is on form-fit and force-fit connections. An analysis of the connectors used in the battery environment also shows that the components are not connected using material fit.

Cables are a classic example of polymer–metal composites. There are already several methods for recovering the raw materials. The stripping process is used as a mechanical process for large diameters [7]. For smaller diameters, the cables are shredded and then finally ground, often using ball or hammer mills. The polymer and metal are then separated from each other using density separation processes or magnetic separators [8]. The freezing process, in which the brittleness of the polymers is increased and the impact strength of the polymer is reduced by low temperatures, is also very suitable. The properties of the copper are retained, making it easier to separate the polymer from the metal in a mill. In water jet technology, the materials are cut using water pressure. In cable recycling, chemical and thermal processes are also used to separate the polymer from the metal. This involves either immersing entire cables in chemical solutions or burning them in a cement oven [6]. The German Federal Environment Agency has published statistics showing that 64% of all polymer waste was recycled for energy in 2023 [9]. However, the polymer cannot be reused for new polymer components in this way, which is why our focus is on mechanical processes.

In Knappich et al. [10], galvanized polymer components are first pre-shredded in a cutting mill and the shredded material is then subjected to further stress in a hammer mill. Cryogenic temperatures and high impact speeds have a positive effect on material disintegration. However, cryogenic temperatures also lead to finer particles [10]. Hammer and impact mills were chosen in this work because the corresponding composite parts from the battery environment are form-fit and force-fit connected and not material-fit connected as in the case of the galvanized waste. The polymer is to be separated from the metal by impact stress. The metal components do not necessarily have to be shredded. The metal cores of the components are too solid for cutting stress, which would result in enormous wear.

Impact and hammer mills both belong to the class of impact crushing machines, which differ in their crushing tools [11]. In the impact mill, the impact bars are firmly connected to the rotor. In the hammer mill, the hammers are movably mounted on the rotor. Both types can have impact bars in the crushing chamber, as well as the option of installing sieve grids for sizing. Impact mills are particularly suitable for medium-hard and hard brittle materials, whereas hammer mills are preferable for soft to medium-hard materials [10]. The material to be ground is stressed by the rotating tools. Compared to other types of mills, comparatively high peripheral speeds are possible in both mills, so that a high throughput and a high crushing ratio can be achieved. Metallic materials can also be shredded, but the wear on these shredders is then also very high [12]. Boekhoff et al. [13] shows that the success of the impact crushing of polymer plates depends on the temperature and humidity of the sample. The lower the temperature, the better the polymer can be crushed; more moisture in the polymer's structure leads to difficulties during crushing. Overall, a correlation was observed between a high Young's modulus and a higher amount of small particles in the crushed material [13].

In order to quantify a recycling process, the recycling efficiency can be used. This is calculated as follows, according to [14]:

$$\text{Recycling efficiency} = (\text{output material mass})/(\text{input material mass}) \quad (1)$$

The formula can be transferred so that the degree of disintegration can be determined. The polymer that can be separated from the metal is the material output. The total amount of polymer mass processed in the composite is the material input. This results in the following formula, which is used to present the results in this paper:

$$\text{Degree of disintegration} = (\text{fully disintegrated polymer mass})/(\text{total polymer mass}) \times 100 \quad (2)$$

Fully disintegrated polymer mass, in this case, means the amount of polymer mass that could be separated from the metal during crushing, i.e., that is present individually, regardless of the size of the individual polymer particles. If the degree of disintegration is 100%, the materials have been completely separated from each other. With a degree of disintegration of 0%, no polymer could be separated from the metal. The higher the degree of disintegration, the better the crushing works in terms of successful recycling [14].

This paper shows the first results of the crushing with defined manufactured samples in order to investigate the direct influence of the joining mechanisms of metal–polymer composites on the crushing properties as well as the effect of the crushing parameters. As no similar studies could be found through extensive research, this topic is important to look at in order to improve recycling. Based on these investigations, recommendations for a design for recycling can be made in order to utilize this knowledge directly at the beginning of the design phase of new components. For existing components, the results of this paper show a way for the components to be crushed in order to achieve the highest possible degree of disintegration with one crushing step. The materials can be separated from each other afterwards and returned to the material cycle as recycled material.

2. Results

In the following, the degree of disintegration was calculated for different samples and is shown in column diagrams. First, the influence of the joining process is considered, and second, the influence of the two different rotors is considered. In addition, the experiments are also performed with two different polymers. Conclusions are then drawn for the design for recycling and initial recommendations are made.

2.1. Influence of Joining Process

The composite components are crushed separately in the mill. The three different parts having different joining mechanisms were manufactured with the material polypropylene, in this case. The samples were crushed in the mill at an outside temperature of 10 °C and a low temperature of −95 °C for embrittlement of the polymer. The hammer and the impact rotor were used, and the results are shown in Figure 1. It shows the degree of disintegration for the different parameter sets, calculated from the mass of the separated polymer in relation to the total mass of polymer on the component, as shown in Formula (2).

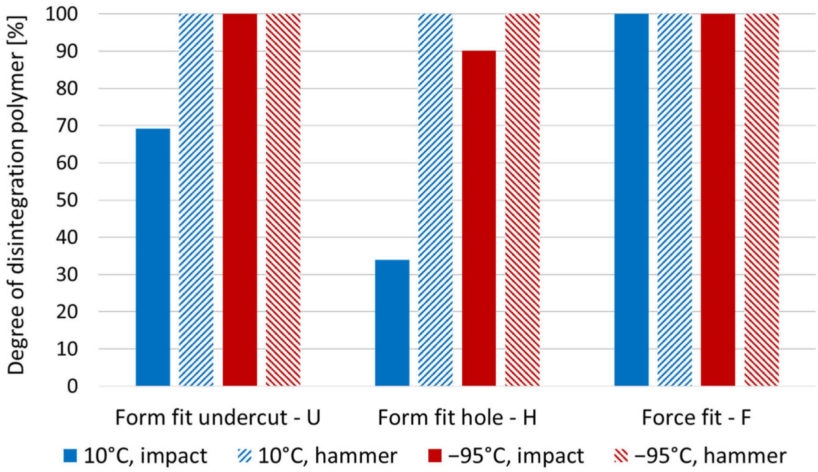

Figure 1. Degree of disintegration of demonstrator component with PP.

Looking at the results with the hammer rotor first, we can see that for every joining process, a full separation for the materials could be achieved. For the impact rotor, we see differences in the degree of disintegration between the different joining types. In the case of "F", also for the impact rotor, a complete separation could be achieved for both temperatures. Meanwhile, for the other connection types, the metal and polymer could not be completely separated from each other with the impact rotor. For the connection type "U", only 70% of the polymer could be separated from the metal; for the connection type "H", approximately 35% could be separated. Therefore, the complexity of the joining process has a significant influence on the disintegration characteristics of the material using the impact rotor, i.e., for the force-fit samples "F", a single fracture is sufficient for a complete disintegration while, for the other connection types, only multiple fractures ensure a complete disintegration. As a result, the adhesion forces that have been established between the polymer and the metal for a force-fit connection are loosened by a single impact or stress event, respectively, and are no longer sufficient to maintain the bond. In the case that not all polymer is released, the metal piece can be separated from the polymer coating by the further application of a relatively small stress. Regarding the form-fit connection, the geometry prevents the metal insert from slipping out and the connection is maintained. If a crack forms and spreads in the polymer due to the stress in the mill, the shape of the metal insert will prevent the connection from loosening. In this case, the polymer pieces must have several fractures to open the form-fit connection.

The use of liquid nitrogen causes the polymer to become brittle. This should make the polymer easier to break and flake off the metal. Due to the different coefficients of thermal expansion of steel and the polymers polypropylene and polyamide 6 (steel: 13×10^{-6}/K, polymers see Table 1), the strong cooling, additionally, generates inner stresses that also contribute to the polymer flaking off the metal. Steel shrinks faster than PP, resulting in tensile stresses in the polymer PP. The coefficient of thermal expansion of PA6 is the highest of the three materials; it shrinks faster than steel, resulting in compressive stresses in PA6. Cooling, and the resulting stresses, can lead to deformations or cracks in the polymer, which could affect the strength of the composite [14]. Nevertheless, the changed mechanical properties of the polymers due to cooling will have a stronger influence on the crushing results than the interfacial tensions. It can be seen that the components cooled with liquid nitrogen and crushed with the hammer rotor still achieve a degree of disintegration of 100%, regardless of the joining process used. This result was to be expected, as the disintegration was already successful even at ambient conditions. In contrast, a clear change can be observed when using the impact rotor. The degree of disintegration increased with the use of liquid nitrogen for both variants of the form-fit connection, i.e., under these conditions, a complete disintegration could be achieved for the connection type "U". In the case of connection type "H", around 90% of the polymer could now be released from the metal, while at ambient temperature, this value was just above 30%.

Table 1. Material properties of Polypropylene and Polyamide 6.

	Polypropylene PP [15]	**Polyamide 6 PA6 [16]**
Density	900 kg/m^3	1130 kg/m^3
Melting temperature	154 °C	220 °C
Young's modulus	1450 MPa	900 MPa
Strain at break	>50%	>50%
Charpy notched impact strength	8 kJ/m^2	30 kJ/m^2
Thermal expansion coefficient	160 × 10^{-6}/K [17]	12 × 10^{-5}/K

The mechanical properties of the polymers have also changed due to the cooling. The Young's modulus increases with decreasing temperatures; the elongation at break decreases and the notched impact strength also decreases [13]. As a result, several fracture events occur during crushing, so that the polymers are broken into finer particle sizes and the form-fit connections are easier to separate than they are at ambient temperature. Only in the case of the connection type "H" could the material bond not be separated in the area of the hole, meaning that a complete separation could not be achieved here. Figure 2 shows an example of the particle size distributions for the components produced with polypropylene and crushed with the impact rotor at 10 °C and at −95 °C, to demonstrate the effect of cooling. Three components of every variant were crushed, and the diagram shows the average particle size distribution. In particle size distribution diagrams, the distribution sum function $Q_r(x)$ is plotted over the sieve mesh size x. Index r indicates the quantity type; index 3 stands for the mass. Accordingly, the ordinate shows the mass percentage of the total mass of the particles that pass through the sieve with mesh size x [18].

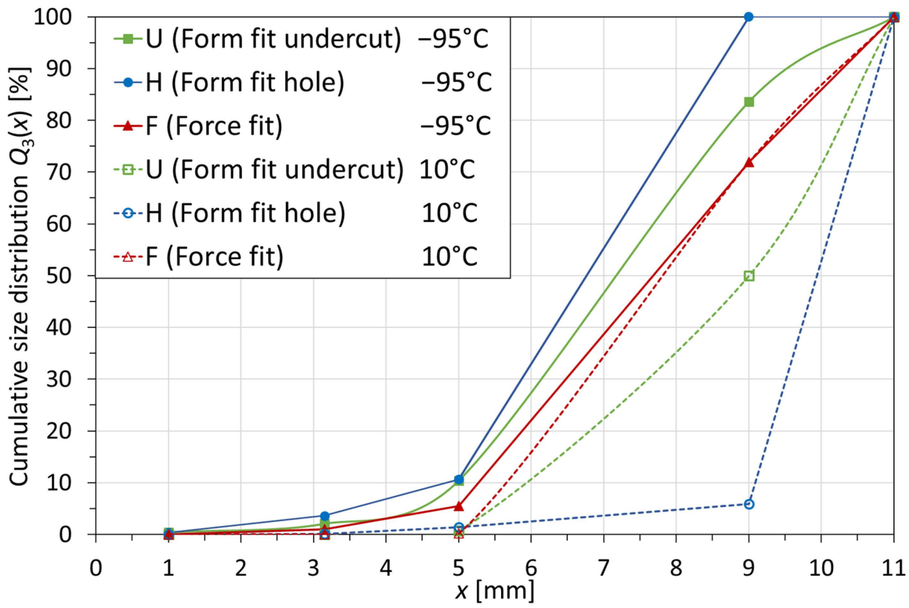

Figure 2. Particle size distributions of polypropylene components crushed with impact rotor at different temperatures.

The two curves for the 10 °C and −95 °C crushing temperatures are very close to each other for the force-fit connected components "F", i.e., no significant improvement could be achieved with liquid nitrogen. The degree of disintegration was already 100% at 10 °C, so that no change could be achieved by cooling (see Figure 1). The more complex the joining process, the greater the difference in particle size distribution due to cooling.

With connection type "U", it was possible to detach parts of the polymer from the metal insert at an outside temperature of 10 °C. Cooling with liquid nitrogen increased the degree of disintegration and also changed the particle size distribution, which can be seen in a higher proportion of fine material for the cooled samples, the graph for which is also located above the two force-fit connected components. In the case of the form-fit connected composites, only just under 30% of the polymer could be detached from the metal at an ambient temperature of 10 °C (see Figure 1). The particle size distribution (Figure 2) shows that the least amount of fine material was present in this experiment. Due to the cooling and the resulting embrittlement of the material, it was now possible to increase the degree of disintegration to approx. 90%. The curve in the particle size distribution is even higher than the curve for type "U". Not only was the proportion of fine material highest at −95 °C for this specimen, but also, the achievable difference between 10 °C and −95 °C crushing temperature was highest here. Due to embrittlement, several fracture events can, presumably, occur simultaneously when the metal piece hits the impact bars. The metal and polymer are then separated instantly from each other for type "F". The mass of the polymer alone is afterwards too low to break further in a second impact event in the mill. For both form-fit connections, the polymer remained on the metal after the first impact. By further stressing the composite by the impact bars inside the milling chamber, cracks could again be introduced into the polymer, thereby increasing the degree of disintegration and the amount of fine material.

For a better visualization of the results, Figure 3 shows photos of the crushed components. These illustrate the results just discussed, for the three components crushed for each variant. The first line shows the results at a crushing temperature of 10 °C and the second line shows the results at a temperature of −95 °C. The particle size distribution clearly differs between the two temperature variations.

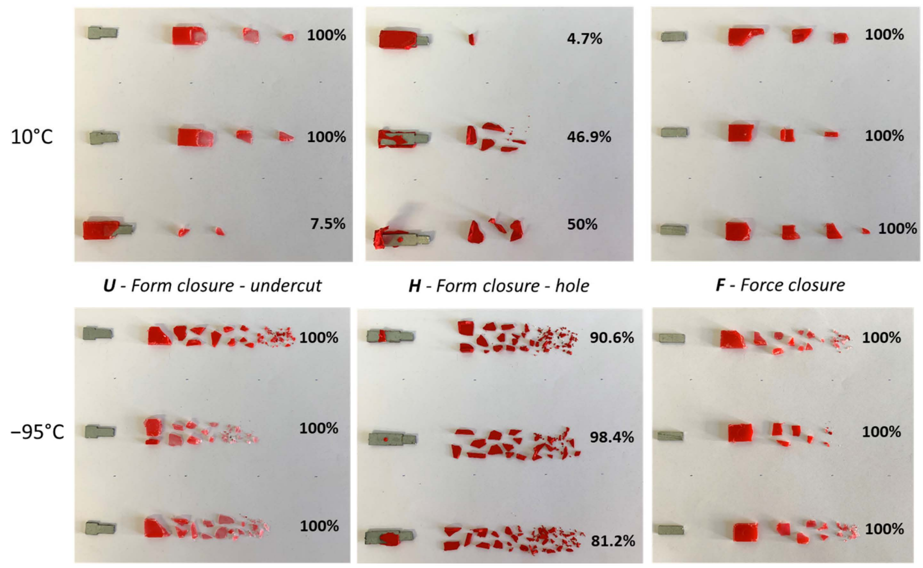

Figure 3. Pictures of crushed composites made of polypropylene including the degree of disintegration, crushed with the impact rotor at two different temperatures.

The pictures visualize the graphs in Figure 2: the difference in particle size between the components connected with type "H" is greatest at the two different temperatures. It was particularly difficult to separate the polymer from the metal in the area of the hole. All samples show comparable results at −95 °C; only the samples crushed at 10 °C show two irregularities, as less polymer could be removed from one component of "U" and "H" than from the other two components.

2.2. Influence of Rotor Type

The previous investigations showed that the results of the two different rotors differ significantly. Figure 4 presents a more detailed investigation in the form of particle size distributions that were undertaken with pure polymer plates made of PA6. Again, the experiments were carried out at 10 °C and at −95 °C.

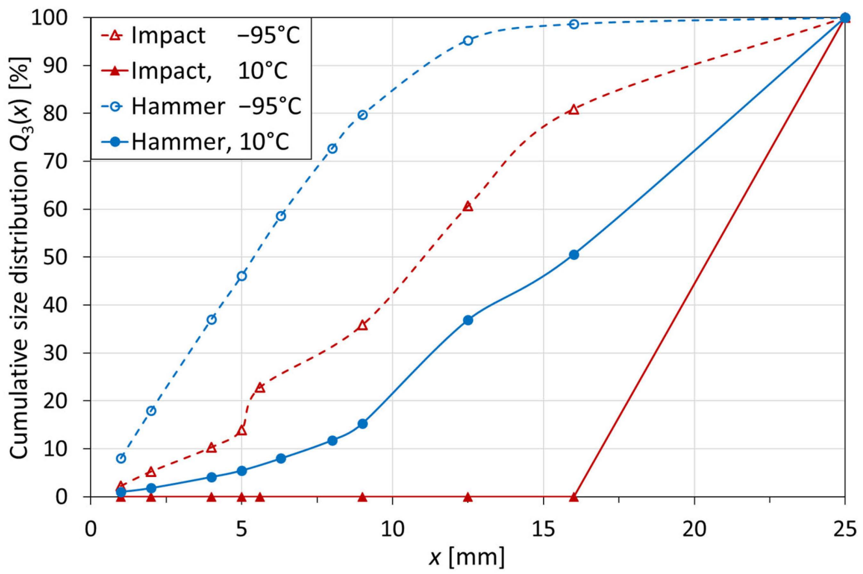

Figure 4. Particle size distribution of polymer plates of PA6, crushed with both rotors.

The particle size distributions show that pure polymer plates, i.e., no composite, can also be crushed better with the hammer rotor. At an outside temperature of 10 °C, small particle sizes could be produced with the hammer rotor, while with the impact rotor, the polymer plates could not be crushed at all. When cooled down to −95 °C with liquid nitrogen, finer particles could be achieved with both rotors, as more breakage events occurred. Crushing with the impact rotor at low temperatures was, indeed, more successful than crushing with the hammer rotor at an outside temperature of 10 °C, but when using the hammer rotor at low temperatures, the finest grain spectrum was produced. Thus, the results achieved with the demonstrator composites were confirmed with the polymer plates.

In order to explain the differences, the airflow speed was measured over a time of one minute at the center of the outlet of the mill for both rotors. The results can be seen in Table 2.

Table 2. Airflow speed at the outlet of the mill with the two rotors.

	Outlet Air Speed
Hammer rotor	0.6 m/s
Impact rotor	2.5 m/s

Due to the geometry of the rotor, the impact rotor can accelerate the air significantly more. For the hammer rotor, an average speed of 0.6 m/s was measured, while the measurement for the impact rotor shows a significantly higher air speed of 2.4 m/s. This results in shorter residence times of the material in the crushing chamber equipped with the impact rotor, and, therefore, the particles are drawn out of the mill more easily according to the high airflow. The shorter residence time in the crushing chamber leads to less stress events and, therefore, to a lower degree of disintegration. Although the outer diameters of both rotors are the same when the hammers are set up due to rotation, the inner diameters are not. The hammers have a larger impact area, i.e., the components have a higher probability hitting the impact surface on the rotor and can be transported in the upper grinding chamber better. The fact that there is no discharge sieve in the mill means that the components can quickly leave the mill with the increased airflow of the impact rotor. With a sieve installed, the components would remain in the crushing chamber until they have reached the required fineness to pass the sieve. Then, however, the metal pieces also would have to be broken or at least heavily deformed, which is not desirable and probably also not desirable in this mill.

2.3. Influence of Different Polymers

The force-fit “F” and form-fit connected components with the hole “H” were also manufactured using the material combination steel and Polyamide 6. Here, too, both rotors were used for crushing. Figure 5 shows the difference in the degree of disintegration of the two different materials at a crushing temperature of 10 °C.

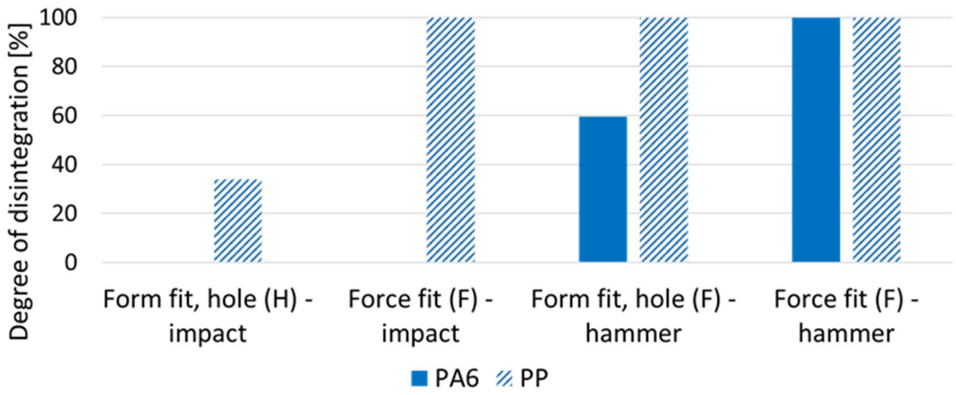

Figure 5. Comparison of the degree of disintegration with the materials PA6 and PP at 10 °C.

When using the impact rotor, it was possible to detach some polymer from the metal using PP. For the force-fit connection “F”, the polymer could even be completely detached from the metal. With the material polyamide 6, no separation could be achieved with either joining mechanism when applying the impact rotor. With the hammer rotor, it was possible to realize a degree of disintegration of 100% for the material PP with both joining processes. For the material PA6, instead, Figure 5 shows that a degree of disintegration of 100% could only be achieved when using the force-fit joining mechanism. Almost 60% of the polymer could be separated from the metal for connection type “H” components.

The difference in the shredding results is caused by the different material properties of PA6 and PP. The material PP has a higher Young’s modulus and a lower notched impact strength than the material PA6 (see Table 1). In [13], it was shown that materials with a higher Young’s modulus tend to be easier to shred. A lower notched impact strength results in a more brittle material behavior, so that lower forces can lead to fracture [13,14], i.e., the combination of a higher Young’s modulus and a low notched impact strength for PP leads to a higher degree of disintegration.

Figure 6 shows the same experiments as Figure 5, but with a crushing temperature of −95 °C. This shows that cooling with liquid nitrogen significantly increased the degree of disintegration in all samples analyzed. The force-fit and form-fit joints could be completely released with the hammer rotor for both PA6 and PP, as well as with the impact rotor for both materials and the force-fit connection. Only in case of the form-fit connection type “H” was it not possible to achieve a degree of disintegration of 100% in the impact rotor for both materials. However, the results at −95 °C are also better than they are in direct comparison with Figure 5, i.e., crushing at 10 °C.

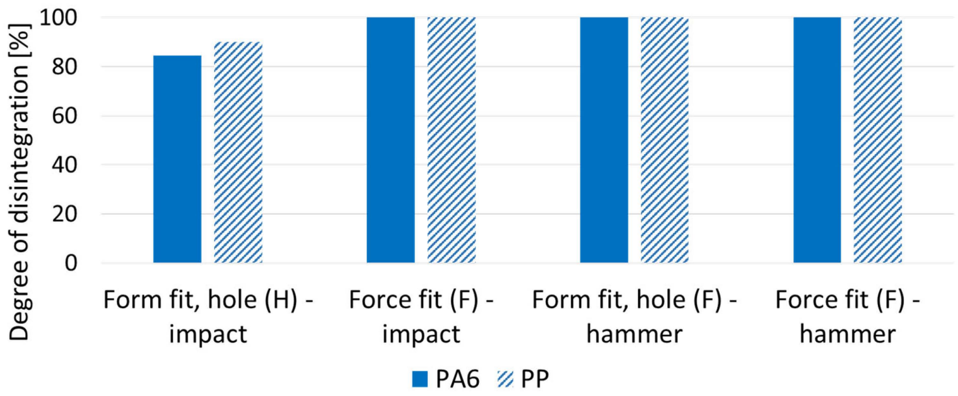

Figure 6. Comparison of the degree of disintegration with the materials PA6 and PP at −95 °C.

3. Materials and Methods

3.1. Component Setup and Materials

For the experiments, a demonstrator component was designed and manufactured. A modular injection molding tool can be used to implement various joining processes with different materials. Figure 7 shows a schematic of the used options. The selected geometry of the components is inspired by industrial components in order to generate a representation of the parts as accurate as possible. To produce to components, the different variants of the metal inserts were first cut to size. The metal inserts were then inserted into the injection mold and heated to the mold temperature and, then, the melted polymer was injected around the metal part.

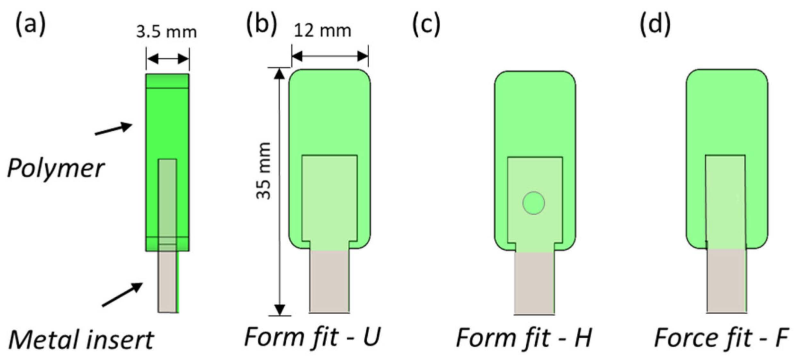

Figure 7. Demonstrator component with different joining processes ((**a**): side view; (**b**): form fit connection through undercut; (**c**): form fit connection through hole; (**d**): force fit connection).

The side view of the component is shown in Figure 7a; the metal insert is grey and the over molded polymer is shown in green. The joining process can be changed by changing the geometry of the insert. A form-fit connection is created if the insert has an undercut or a hole, as shown in Figure 7b,c. For a better identification during the following result discussion, the component with the undercut is later abbreviated to "U" and the component with the hole to "H". The polymer with this form-fit connection encases the insert in such a way that it cannot simply be pulled out. Two different form-fit variants were selected to simulate different degrees of connection complexity. The joint with the hole has a higher degree of complexity than the joint with the undercut, as the polymer has to be removed from the hole. In the force-fit connection, a straight metal piece is used (Figure 7d) so that the polymer and the metal are only held together by frictional forces. This component is abbreviated to "F".

As polymers, Moplen HP501H Polypropylene from LyondellBasell and Polyamide 6 unfilled Ultramid B3W from BASF were used. Table 1 shows the mechanical properties of both polymers; however, the thermal expansion coefficient for the PP used was not mentioned in the data sheet, so an exemplary reference value for another PP was used here. The properties of Polyamide 6 depend on the moisture content of the material. The data sheet gives values for both the dry and air humid state, but Table 1 only shows the values for the air humid state. The polymer granulates were conditioned before processing in accordance with the manufacturer's recommendations. The composites were then stored in a standardized climate.

The metal insert is a commonly used steel; DC06 was used for all components, only the geometry was changed. More information about the composition of the steel grade can be found in the data sheet in source [19]. Steel has a thermal expansion coefficient of 13×10^{-6}/K and, thus, between that of the two polymers [20]. For further experiments with the different rotors, polymer plates of the material PA6 were used with the geometry 50 mm × 50 mm × 4 mm.

3.2. Mechanical Crushing

For mechanical crushing, a rotor impact mill (No. 9459, Company Hazemag, Dülmen, Germany) was used. Two different rotors were applied for the experiments: first, an impact rotor with four continuous, permanently mounted beater bars on the rotor; second, a hammer rotor with 24 free-moving hammers on four rows. The comparison of the two rotors, which are suited for different materials, is intended to show which is more appropriate for a composite. Figure 8 depicts both rotors; on the left, the hammer rotor, and on the right-hand side, the impact rotor. Both rotors have an outside diameter of 288 mm and a resulting circumferential speed of 21.1 m/s. The rotational speed of 1400 rpm is constant and cannot be varied. The components are fed to the running mill individually, three for each experiment. The components are crushed in the mill and leave through an outlet without a screen. Therefore, the metal parts can leave the mill without a size reduction. After the crushing process, the material is analyzed, and the degree of disintegration is calculated based on the weights. Crushing takes place at an outside temperature of 10 °C. An air flow meter (testo 440 climatic measuring instrument, company testo, Hampshire, UK) was used for air flow measurements at the outlet of the mill.

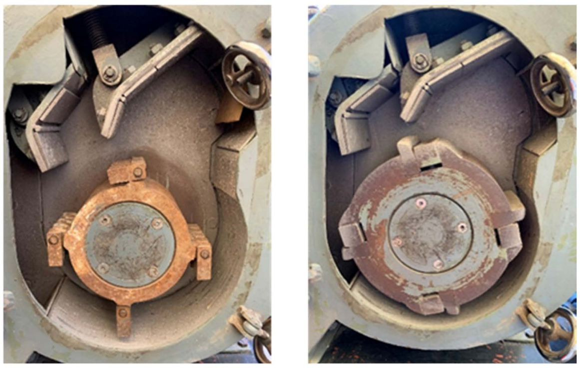

Figure 8. Inside view of the mill (**left**: hammer rotor; **right**: impact rotor).

Furthermore, the influences of low temperatures on the disintegration were investigated by cooling the components before they were crushed in the mill with the different rotors. Sudden cooling was achieved by immersing the samples in a bath of liquid nitrogen. The samples were stored there for a few minutes until the components were fully cooled. The surface temperature was measured using a laser thermometer after removal from the nitrogen bath and insertion into the mill and was always in the range of −95 °C (± 5 °C). By cooling the samples, the polymer becomes brittle and it is easier to separate metal and polymer from each other.

The particle size distributions were determined by sieving the crushed material with a sieving machine (AS200 control, company Retsch, Haan, Germany). The following sieve sizes were used for the single polymer plates: [1; 2; 4; 5; 6.3; 9; 12.5; 16] mm. For the smaller demonstrator components, the sieve sizes were [1; 3.2; 5; 9] mm.

4. Conclusions and Outlook

In order to successfully recycle composite components, it is important that all materials are separated from each other by type. To do this, the previously produced material bonds must be broken or separated, respectively. To be able to proceed as effectively as possible in the recycling process and to consider successful recycling as early as possible in the development phase, it is important to know the influence of different joining processes used in the industry on the crushing properties. For this reason, demonstrator components were used in this work, which connected the polymer and metal components in two variants: one with a force-fit connection and others with form-fit connections. These components were crushed in mills with an impact rotor or a hammer rotor at two different temperatures. The experiments showed that the joining process influences the degree of disintegration. The embrittlement of the polymer due to liquid nitrogen led to increased degrees of disintegration in the form-fit connected components and to smaller particles. The use of the different rotors shows the performance of the hammer rotor for detaching the polymer from the metal inserts. Due to the geometry of the impact rotor, the speed of the airflow is too high, so that the components stay in the mill too briefly, and, thus, not enough stress events with sufficient stress intensity occur in the mill before they leave the crushing chamber.

Moreover, conclusions for a design for recycling can be drawn from the crushing results. The comparison of the different joining methods has shown that it is easier to separate components that are joined by force. The degree of disintegration was the highest for force-fit connected components for both rotors, meaning that a force-fit connection should be favored. If the requirements for the component do not permit a force-fit connection, it should be considered that the form-fit connection be selected instead, as it has the least-possible complexity. It has been shown that the polymer particles cannot be released from the metal inserts, or can only be with great difficulties, especially in the area around and in the hole of the metal insert. By using an undercut for the metal component, the quality of the connection could be increased compared to the force-fit connection, while at the same time, complete material disintegration was possible here. On the material side, it can be stated that different materials exhibit different crushing behaviors. Therefore, as far as possible, care should be taken to ensure that individual components are made, preferably, of just one polymer type and do not consist of composites made from different polymers. This also facilitates the subsequent sorting process, as polymers must be separated from each other by type so that recycling can be realized much easier.

Further experiments could deal with the further processing of the separated polymer. In regard of a circular economy, further research should also focus on the question of to what extent the polymer needs to be purified or how a second crushing step should be designed before the material can be fed back to the injection molding system. Equally of interest would be the subsequent sorting process, in which the polymer, metal and remaining composite fractions have to be sorted.

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