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On the impact of recycling strategies on energy demand and CO_2 emissions when manufacturing Al-based components

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Abstract

The industrial world is facing the challenge of reducing emissions by means of energy- and resource-efficient manufacturing strategies. In some cases, the exerted emissions and the energy demands related to conventional manufacturing processes are not as intensive as those required to extract and produce the raw materials of which the workpieces are made. Therefore, the consciousness of the impact of material usage and the eco-informed choice of the end-of-life scenarios are both needed in view of sustainable development. Aim of this paper is to offer a contribution to a better understanding of the environmental impact of forming and machining processes, for the production of Al-based components, when varying the aluminum recycling strategy.

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Keywords: Sustainable manufacturing; Recycling; Aluminum; Machining; Forming.

1. Introduction

Industry accounts for almost 40 % of the World's direct and indirect CO_2 emissions, and the contribution due to the electricity usage represents the 18 % of the total amount [1]. A relevant share (around 20 %) of CO_2 emissions is attributable to the material production [2], which is dominated by few material categories: steel, cement, paper, aluminum, and aggregated plastics. Moreover, from 2005 to 2050, aluminum demand will grow of a factor between 2.6 and 3.5 [3]. Material processing industry has to deal with materials and energy reduction targets. In addition, raw materials, gas, and electricity prices have been rising over the last years [4]. A full awareness about the environmental impact of all the existing technologies should be available [5]. The growing interest in quantifying the CO_2 footprint led to the development of a methodology for the systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) [6]. A state of the art concerning energy and resource efficiency studies in the manufacturing domain was presented by Duflou et al. [7]. Nevertheless, the studies on sustainability analysis of metal shaping technologies focus mainly on material removal processes. According to Dahmus and Gutowski [8], the system-level environmental analysis of machining includes all the activities related to material removal, tool preparation, machine tool construction, cutting fluid preparation, and part cleaning. The environmental impact deriving from the material removal operations is primarily due to the energy consumption, and the energy demands of the auxiliary equipment can far exceed the cutting energy requirements [9, 10]. Models are available in literature, either for estimating the specific energy consumption [11, 12] or for computing the total direct energy requirements [13, 14]. Moreover, the shortening of machining time by increasing process parameters must not compromise tool life or surface quality [15].

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Few studies in the domain of environmental performance analysis of metal forming processes have been published. A review in the field of sheet metal forming was developed by Ingarao et al. [16]. A comprehensive study on air bending process can be found in Santos et al. [17]. Other authors focused on the environmental analysis of incremental forming [18, 19], or on sheet metal forming process chains [20]. A holistic study concerning the environmental issues of bulk forming processes was developed by Buis et al. [21]. Besides machining and forming, some researchers focused also on non-conventional [22] and additive manufacturing processes [23]. Overall, three main approaches to manufacture a metal-based component could be applied: mass conserving (e.g., forming), subtractive (e.g., machining), and additive processes. Each approach is characterized by a different amount of material usage. To properly evaluate the environmental impact of a given process, a standing-alone approach is no longer sufficient. However, only few studies have already been developed by using comparative methods [24, 25].

The present paper represents an effort aimed at tuning a methodology able to thoroughly analyze the impact of machining and forming processes. The proposed comparative study enables the energy and carbon footprint quantification for both the manufacturing approaches. An in-depth analysis on life cycle material accounting is presented, and the environmental performance is assessed and compared with varying material usage-related factors.

2. Methodology

A methodology for comparing the environmental impact of forming and machining processes was proposed lately by the authors [26, 27]. The production of an axy-symmetric shaped component made of an AA-7075 T6 aluminum alloy was assumed as case-study. A single-step hot extrusion (bulk forming) process and a machining (turning) process were compared. As a matter of fact, various mechanical components can be manufactured using both the approaches. Often, the process choice is driven either by cost or production rate requirements. The present research aims at including also environmental-related indicators in the decision step.

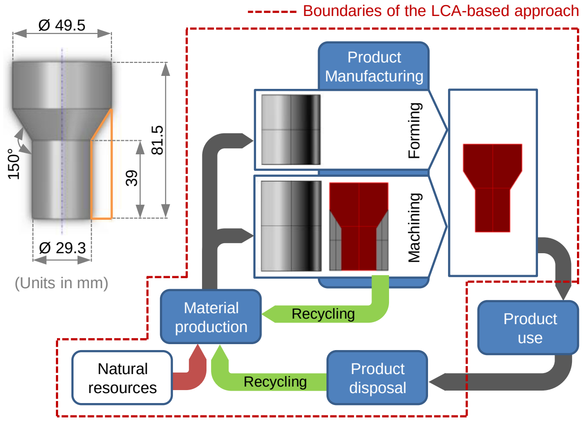

Fig. 1. LCA-based approach for process comparison.

In order to account for the environmental burden of all the product life-cycle phases, the LCA-based approach shown in Figure 1 was considered. The single component production (within a defined batch size) was assumed as a basis for processes comparison. The energy flows and the (carbon-equivalent [2]) CO_2 emissions occurring during the material production, the product manufacturing, as well as the end-of-life phase were included in the study. For material production, the embodied energy (i.e., the energy committed to create 1 kg of usable material from its ores and feedstock [2]) has been considered. The use phase was overlooked, as it was assumed to be identical for both the products obtained by the two technologies [26]. Former results proved that workpiece material usage has a significant effect on the environmental impact, even varying factors of influence as production batch size and part geometry [27]. Thus, the impact assessment of the aluminum recycling strategy is of primary importance, and the related benefits should be accounted for.

2.1. Material production and recycling benefit awarding

When material recycling is neglected, the energy due to the workpiece material production is computed according to Equation 1. The energy consumed to produce the workpiece (E_M, in MJ) is the product of the workpiece weight (m_w, in kg) and the embodied energy (for primary production) of the material of which the workpiece is made (H_V, in MJ/kg). Hence, mass-conserving processes are expected to have a lower material-related impact in comparison to material removal processes, as machining, which produce material scraps in the form of chips. The CO_2 emissions (in kg) can be similarly assessed, as shown in Equation 2.

$$E_M = H_V \cdot m_w \qquad (MJ) \tag{1}$$

$$CO_{2M} = CO_{2V} \cdot m_w \qquad (kg) \tag{2}$$

As far as material recycling is concerned, it is worth remarking that there is no a single criterion to account for recycling credits. Nevertheless, some useful guidelines were provided [28]. Two principal methods dealing with the environmental credits arising from recycling exist: the recycling content approach and the substitution method. The first one ascribes the full benefits of material recycling to the start of its life, neglecting the benefits arising from the end-of-life recyclability. Vice versa, the second one allocates the environmental credit of recycling to the end-of-life stage. The substitution method, which is applied in the present paper, considers the impacts on the present climate to produce and supply the material (cradle-to-gate), and gives a recycling credit for future recyclability (end-of-life). For materials that have no losses in inherent properties (i.e., for materials that guarantee a comparable mechanical performance when obtained from both primary and secondary production), the embodied energy calculated by the substitution method (H_{SM}, in MJ/kg) can be computed with reference to Equation 3, where the fraction of recycled material at the end-of-life (r) and the embodied impact arising from recycled material input (H_R, in MJ/kg) are included.

$$H_{SM} = r \cdot H_R + (1-r) \cdot (H_V + H_D) \qquad \left(\frac{MJ}{kg}\right) \tag{3}$$

If the energy needed for disposal (H_D) is neglected, as in case of most metallic materials, Equation 3 could be rewritten in Equation 4, where the embodied energy savings ($H_V - H_R$, in MJ/kg) are directly proportional to the material recyclability (r).

$$H_{SM} = H_V - r \cdot (H_V - H_R) \qquad \left(\frac{MJ}{kg}\right) \tag{4}$$

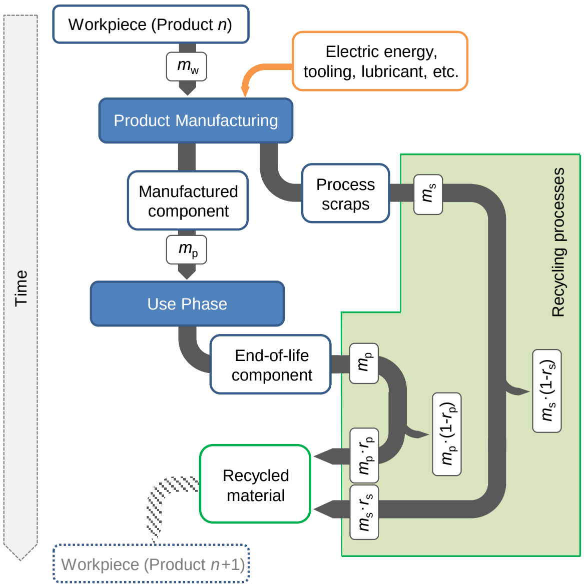

Fig. 2. Application of the substitution method to account for recycling.

Moreover, when considering a system in which different kinds of material scraps are produced at different life-cycle stages, all the various contributions to the material recycling have to be added. The approach shown in Figure 2 has been applied to the present case study. The component (weighing m_p, in kg) is produced from a workpiece (weighing m_w, in kg) via forming or machining. The process scraps (i.e., the chips obtained as by-product when turning) as well as the component (which is disposed at the end of its first life) are assumed to be recycled. In the model, it has been supposed that the weight (m_p) of the component remains unchanged during the use phase. The amount of material effectively recycled from both process scraps ($m_s \cdot r_s$) and bulk material ($m_p \cdot r_p$) will contribute to produce another workpiece. Therefore, according to the substitution method, the energy for the workpiece material production (E_M, in MJ) and the resulting CO$_2$ emissions (CO_{2M}, in kg) were assessed applying Equation 5 and Equation 6, respectively.

$$\begin{aligned} E_M &= H_V \cdot m_w + \\ &- r_p \cdot (H_V - H_{R,p}) \cdot m_p - r_s \cdot (H_V - H_{R,s}) \cdot m_s \qquad (MJ) \end{aligned} \tag{5}$$

$$\begin{aligned} CO_{2M} &= CO_{2V} \cdot m_w + \\ &- r_p \cdot (CO_{2V} - CO_{2R,p}) \cdot m_p + \\ &- r_s \cdot (CO_{2V} - CO_{2R,s}) \cdot m_s \qquad (kg) \end{aligned} \tag{6}$$

As far as the material recycling strategy is concerned, different solutions are considered in the present paper, as detailed in Section 2.2.

2.2. Aluminum recycling processes

The aluminum recycling processes deserve a digression. Secondary aluminum production from scrap by traditional remelting requires much less energy than primary production. Despite that, the aluminum recycling process is still an energy-intensive one, and the overall energy efficiency is very low. Moreover, an even more relevant issue concerns the permanent material losses occurring during remelting, because of oxidation. This aspect is particularly relevant for chips: light-gauge scraps, having a high surface area-to-volume ratio, tend to float on the surface of the melt, causing a significant oxidation that can be as high as 15-20% [29, 30]. By avoiding remelting, significant amounts of both energy and material can be saved. Recently, various solid state recycling approaches have been developed [31, 32]. The use of hot extrusion as recycling method is so far the most analyzed one [32]. This envisages turning chips directly into fully dense profiles by a cold compacting step followed by a hot extrusion one. In this paper, both conventional and solid bonding recycling methods are considered. Table 1 lists all the ecological properties of the AA-7075 aluminum alloy. The data concerning the primary production and the conventional recycling were found in CES EduPack [33]. Data regarding the solid bonding approach (compacting as well as hot extrusion) were modelled starting from information available in literature [34, 35].

Table 1. Ecological properties for the AA-7075 alloy [33-35].

Eco-property		Symbol (UM)	Value
Primary production	Embodied energy	H_V (MJ/kg)	202.0
	CO$_2$ footprint	$CO_{2\,V}$ (kg/kg)	12.7
Conventional recycling (CR), i.e. remelting	Embodied energy	H_R^{CR} (MJ/kg)	34.3
	CO$_2$ footprint	$CO_{2\,R}^{CR}$ (kg/kg)	2.7
	Recyclability (bulk)	r_p^{CR}	0.95
	Recyclability (chips)	r_s^{CR}	0.85
Solid bonding recycling (SB)	Embodied energy	H_R^{SB} (MJ/kg)	7.3
	CO$_2$ footprint	$CO_{2\,R}^{SB}$ (kg/kg)	0.87
	Recyclability (chips)	r_s^{SB}	1.00

2.3. Energy for manufacturing

The experimental set-up described in [26] was considered. When machining, turning tests were performed on a Cortini F120/25 CNC lathe. When forming, a four pillars electro-hydraulic Instron 1276 machine with a load capability of 1000 kN was used. Materials and energy consumed in each manufacturing stage were monitored, and the related impacts were quantified. The electric energy demand for processing was measured with respect to productive and non-productive operational modes. In addition, the energy footprint for tooling was considered for both the processes, as detailed in the following sub-sections.

2.3.1. Machining

For machining, the energy demand for manufacturing ($E_{MFG}{}^{m}$, in MJ/part) has been computed as shown in Equation 7. The contributions of both cutting (E_C) and non-cutting (E_{NC}) operations are included in the assessment of the electric energy consumption of the machine tool ($E_{MT}{}^{m}$). In addition, the cutting tool footprint ($E_{tooling}{}^{m}$) is considered. In Equation 7, all the contributions should refer to their energy source consumption. Therefore, the energy conversion coefficient η has to be introduced, in order to account for the energy losses occurring at the various steps of the production of electricity from primary energy sources.

$$E_{MFG}{}^{m} = \frac{E_{MT}{}^{m}}{\eta} + E_{tooling}{}^{m} = \frac{(E_C + E_{NC})}{\eta} + E_{tooling}{}^{m} \qquad \left(\frac{MJ}{part}\right) \tag{7}$$

The total cutting tool footprint can be expressed by the summation in Equation 8. Each *i*-th addend is related to the footprint of each *i*-th cutting tool applied in the manufacturing route (i.e. for roughing, semi-finishing, or finishing operations). The ratio between the embodied energy of the cutting tool (E_{ct}, in MJ/insert) and the number of cutting edges (n_e) which can be exploited prior to worn insert substitution expresses the embodied energy per cutting edge (in MJ/edge). This value has to be multiplied by the ratio between the cutting time (t_c, in min) and the tool life (T_L, in min). For the present case study, the machining of the part was performed by means of two subsequent operations of roughing and finishing (by using two different tools, characterized by $n_e = 2$) [26].

$$E_{tooling}{}^{m} = \sum_{i=1}^{n}\left(\frac{E_{ct}}{n_e}\cdot\frac{t_c}{T_L}\right)_i = \left(\frac{E_{ct}}{n_e}\cdot\frac{t_c}{T_L}\right)_{roughing} + \left(\frac{E_{ct}}{n_e}\cdot\frac{t_c}{T_L}\right)_{finishing} \qquad \left(\frac{MJ}{part}\right) \tag{8}$$

The approach in Equation 8 has been applied in the present paper, and it can be used regardless of the production batch size. Actually, the energy used to produce a cutting tool is spread over each manufactured component, on the basis of the tool consumption ratio. It is worth pointing out that in [26, 27] the authors proposed a slightly different methodology to account for the batch size. However, the differences among the two methodologies in terms of cutting tool footprint have proved to be almost negligible. For machining, the data collected during the Life Cycle Inventory (LCI) are listed in Table 2. The embodied energy per cutting insert E_{ct} (i.e., the embodied energy of cutting tool material plus the energy for cutting tool production) and the tool life T_L were assumed to be equal for both roughing and finishing cutting tools ($E_{ct}{}^{r} = E_{ct}{}^{f}$; $T_L{}^{r} = T_L{}^{f}$).

Table 2. Life Cycle Inventory for machining process.

Variable	Symbol (UM)	Value
Cutting time, roughing operation	$t_c{}^{r}$ (min)	1.0
Cutting time, finishing operation	$t_c{}^{f}$ (min)	0.5
Cutting time, total	t_c (min)	1.5
Non-productive time, total	t_{np} (min)	1.0
Electric energy demand, machine tool	$E_{MT}{}^{m}$ (MJ/part)	0.30
Embodied energy per cutting insert	$E_{ct}{}^{r} = E_{ct}{}^{f}$ (MJ/insert)	5.5
Tool life	$T_L{}^{r} = T_L{}^{f}$ (min)	15.0

Table 3. Life Cycle Inventory for forming process.

Variable	Symbol (UM)	Value
Electric energy demand, machine tool	$E_{MT}{}^{f}$ (MJ/part)	1.97
Energy for billet heating	$E_{heating}$ (MJ/part)	1.59
CO_2 footprint for billet heating	$CO_{2\,heating}$ (kg/part)	0.08
Energy for punch and die production	$E_{tooling}{}^{f}$ (MJ)	134.4
CO_2 footprint for punch/die production	$CO_{2\,tooling}{}^{f}$ (kg)	10.7

2.3.2. Forming

For forming, with respect to Equation 9, the energy to manufacture each part ($E_{MFG}{}^{f}$, in MJ/part) comprises the electric energy due to the machine tool demand ($E_{MT}{}^{f}$), including both productive and non-productive times, the energy for heating the billet ($E_{heating}$), as well as the energy for tooling ($E_{tooling}{}^{f}$). E_P is the energy adsorbed by the hydraulic press during the tool/workpiece contact, while E_{NP} takes account of the energy for loading/unloading the billet and for the upwards/downwards movements of the punch. As for Equation 7, also in Equation 9 the electric energy demand of the machine tool has been divided by η.

$$E_{MFG}{}^{f} = \frac{E_{MT}{}^{f}}{\eta} + E_{heating} + \frac{E_{tooling}{}^{f}}{N} = \frac{(E_P + E_{NP})}{\eta} + E_{heating} + \frac{E_{tooling}{}^{f}}{N} \qquad \left(\frac{MJ}{part}\right) \tag{9}$$

The environmental impact related to die and punch production was included in the $E_{tooling}{}^{f}$ value. The material usage was assessed by considering the embodied energy of the AISI H13 used for both punch and die. Furthermore, the electric energy demand to machine the final die shape was estimated. When computing the tooling footprint in forming, the credit deriving from AISI H13 recycling were always considered (by applying the above described substitution method). The total energy demand (or CO_2 emissions) due to equipment and tooling have to be divided by the produced batch size (N). The data collected during the LCI phase are listed in Table 3. Obviously, if further post-forming finishing operations are needed, their contributions on energy consumption should be added to that of Equation 9. For the present case study, a turning operation to ensure a satisfactory part quality has been envisaged. However, due to the reduced complexity of the component's shape, its impact to energy demand and CO_2 emissions has proved to be negligible [26].

2.4. CO_2 emissions and CES method

CO_2 emissions where assessed either directly, or via the Carbon Emission Signature (CES) method proposed by Jeswiet and Kara in 2008 [36] to account for CO_2 emissions due to the electric energy consumption. Knowing the energy (E_{MT}) needed to produce (either via forming or via machining) a part, the carbon emitted can be found by using Equations 10 and 11 (where C, G and O are the fractions of coal, gas and oil, respectively, of the Italian mix). The energy conversion coefficient η was assumed to be equal to 0.34.

$$CES = \frac{1}{\eta}\cdot\left(112\cdot C + 49\cdot G + 66\cdot O\right) \qquad \left(\frac{kg}{GJ}\right) \tag{10}$$

$$CO_2 = E_{MT}\cdot CES \qquad \left(\frac{kg}{part}\right) \tag{11}$$

3. Results and discussion

The impacts of both the conventional recycling method and of the innovative solid state one have been modeled, and their influence on the process comparison analysis has been implemented. In order to analyze the influence of the recycling process itself, different scenarios have been hypothesized:

1. credit from recycling not considered;
2. conventional recycling approach for both part material (bulk) and process scraps (chips);
3. conventional recycling approach for part material (bulk) coupled with the solid bonding recycling approach for the machined chips.

The CO_2 emissions arising from the production of a part belonging to a batch size equal to 10 and 100 are shown in Figure 3. In the graphs, for each scenario, the calculated contributions are separately reported, and the impact of each factor of influence can be recognized. Overall, it is possible to state that the impact related to material production is usually dominant. Such statement is particularly true for machining, where the material-related factor accounts at least for 94% of the total emissions across the considered scenarios. Results prove that considering recycling (in general) leads to substantial energy and CO_2 emissions savings. Moreover, solid state recycling enables relevant environmental impact benefits to be obtained, and it even causes the overturn of processes comparison results, despite of the considered batch size.

Figure 4 plots the CO_2 emissions as a function of the production batch size, for both forming and machining. For higher production volumes, the forming approach is generally the greener one. On the other hand, for small batch sizes, the machining process appears to be the best strategy. Tooling has a different influence within the two processes. In the forming one, the tool manufacture has a relevant role in the environmental impact, and such relevance increases with the decreasing of the batch size. For the machining approach, the influence of tooling footprint is much less relevant.

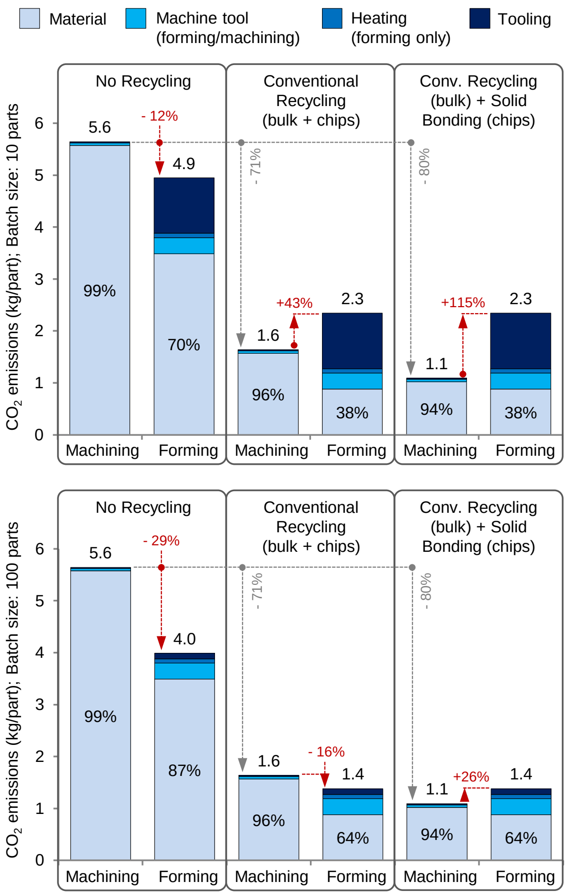

Fig. 3. CO_2 emissions to manufacture (via forming or machining) a part belonging to a batch size of 10 parts (*above*) and 100 parts (*below*).

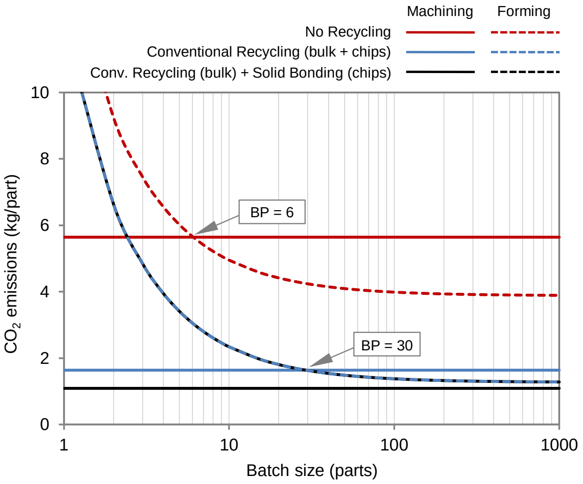

Fig. 4. CO_2 emissions as a function of batch size and recycling scenario.

A Breakeven Point (BP) was identified for all the case studies. The BP is a batch size for which the environmental impact of a component produced by the two different manufacturing approaches is exactly the same. It is possible to notice that, in the worst scenario (Aluminum recycling not considered), the BP is equal to 6 parts. This result is due to the fact that the machined-off material has a higher environmental impact. When the environmental burden ascribed to the machined-off material decreases, the BP increases up to becoming infinite in case of solid bonding recycling.

4. Conclusions

In this paper, the results of an environmental impact comparison between machining and forming are reported. The research regarded an in-depth analysis on the recycling-related issues. The effects of the recycling strategy on the product life cycle environmental impact have been analyzed. The advantages deriving from solid state recycling techniques have been quantified. The influence of recycling policy on the Breakeven Point (batch size for which the environmental impact of different manufacturing approaches is exactly the same) has been discussed. Overall, the more efficient is the recycling process, the more advantageous the machining approach is. The paper therefore highlights the relevance of finding out innovative and efficient recycling strategies in order to lower the overall environmental impact of a product.

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