

# **Manufacturing processes as material and energy efficiency strategies enablers: the case of Single Point Incremental Forming to reshape End-of-Life metal components**

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## **Abstract**

Making materials consumes about 21% of the global energy demand; concerning metals production, it accounts for about 8% of total global energy consumption. Circular economy strategies such as longer life, more intense use, repair, product upgrades, modularity, remanufacturing, component reuse, and open/closed-loop recycling are strategies to put in place urgently to reduce the environmental impact of raw material production. Although recycling of metals is the most used strategy and is being improved in terms of efficiency, it is mandatory moving towards more virtuous circular economy strategies, such as product/component reuse. In this paper a novel reuse strategy for sheet metal based End-of-life components is proposed; to be more specific the suitability of Single Point Incremental Forming (SPIF) to reshape End-of-life aluminum components is presented. An experimental approach is used to change the shape of a square box, previously obtained by deep-drawing processes, by means of single point incremental forming processes.

The paper aims at outlining the environmental impact of the proposed reshaping approach presenting a Cumulative Energy Demand and CO<sub>2</sub>-eq. emissions comparative analysis. Three different routes are analyzed and compared to one another: SPIF based reshaping, conventional recycling and Solid State Recycling (SSR) routes. The SPIF based approach proved to be the most environmentally friendly strategy, the energy and emissions saving are ascribable to the fewer process steps and the less material involved with respect to the analyzed recycling strategies.

## **Keywords**

Circular economy, component reuse, reshaping, energy and resource efficiency

## **Nomenclature**

CE = Circular Economy

BP = Break-Even

SSR = Solid State Recycling

ECAP = Equal Channel Angular Pressing

EoL = End-of-Life

SPIF = Single Point Incremental Forming

CED = Cumulative Energy Demand

CO<sub>2</sub>-eq.= CO<sub>2</sub> Equivalent

R = recycled content (fraction of recycled material in the input material)

r = recyclability (fraction of material recycled at the end-of-life)

ER = embodied primary energy, secondary production

EV = embodied primary energy, primary production

RC = Recycled Content

SA = Substitution Approach

LFR = Lower Feed Rate

HFR = Higher Feed Rate

LCI = Life Cycle Inventory

FEM = Finite Element Method

## 1 Introduction

Making materials consumes about 21% of the global energy demand, and causes about 25% of the global CO<sub>2</sub> emissions (Worrell et al. 2016). Looking specifically at metals production, it accounts for about 8% of total global energy consumption; this energy consumption is expected to increase because of decreasing ore grade (Olivetti and Cullen 2018). Analyzing the energy breakdown analysis of material production, it has been presented that the environmental burden is mainly dominated by five materials: steel (25%), cement (19%), plastics (5%), paper (4%), and aluminum alloys (3%) (Gutowski et al. 2013). In order to both reduce anthropogenic CO<sub>2</sub> emissions and to decouple economic growth from resource consumption, the raw material demand is to be reduced. Strategies to use less material as well as to keep as much material as possible in the circle is, by now, mandatory. Over the last years, the concept of Circular Economy (CE) has gathered momentum (Michael and Rashid 2016). Longer life, more intense use, repair, product upgrades, modularity, remanufacturing, component reuse, and recycling are some of the strategies to put in place to reduce the environmental impact of raw material production (Tolio et al. 2017). As far as metals are concerned, recycling is the most used strategy; in fact, a large number of metals can be recycled at high rates and can be recycled repeatedly. Among metals, lightweight alloys (aluminum, magnesium and titanium alloys) have been under the spotlight over the last decades because of their capability of enabling weight reduction while improving the mechanical performance of structures (Kleiner et al. 2006). For these alloys, recycling allows substantial energy savings with respect to primary production; actually, a reduction as high as 90% can be obtained (Ingarao 2017). Despite these advantages, there is still room for making recycling processes more efficient and less resource demanding. Regarding aluminum alloys (material studied in the present paper), conventional recycling routes are based on re-melting. This process is not efficient in terms of energy demand and, what is more, permanent material losses occur. The high affinity of aluminum to oxygen can lead to permanent material losses during re-melting due to oxidation. These losses can be as high as 15-20% in the case of light-gauge scraps recycling (Duflou et al. 2015). Replacing permanent losses with primary aluminum significantly increases the embodied energy of recycled aluminum. In order to overcome such issues, researchers have turned to Solid State Recycling (SSR) strategies (Wan et al. 2017). The solid-state nature of such a process category results in no material losses. Solid-state consolidation depends on pressure, temperature and contact time among surfaces to be joined. These conditions can be activated by different manufacturing processes mainly relying, either on severe plastic deformation or on sintering processes. Two papers dealt with the environmental benefit quantification of these approaches with respect to conventional re-melting based recycling (Duflou et al. 2015; Baffari et al. 2019)., Both of these studies found out that the best performance of SSR processes is mainly ascribable to the avoided material losses as well as to the reduction of processes steps to get the desired semi-finished product. Although recycling of aluminum is being improved in terms of energy and resource efficiency. It is mandatory moving towards more virtuous circular economy strategies, such as product/component reuse. As a matter of facts, reuse strategies would allow not only material but also the functions to be recovered from End-of-Life (EoL) components. Functions recovery allows further energy saving with respect to recycling as the impact of the manufacturing step to get the final shape is also significantly reduced (Cooper and Gutowski 2017, Zhang et al. 2020).

Cooper and Allwood (2012) presented a reuse framework for metals products/components, in this research the authors identified four main reuse strategies:

- Remanufacture: remanufacturing typically envisages: inspection, disassembly, re-drilling, and metallic spraying/thermal techniques to recover worn and fatigued surfaces. Typical remanufacturing applications for metals concern automotive engines and dies.

- Reshape: reshaping means applying manufacturing approaches (additive, subtractive, mass conserving) to reprocess the returned EoL component changing its shape.
- Relocate: relocating envisages recovering component and applying little refurbishment, such as cleaning and simple repairs and adjustments, when this strategy is applied, the component is normally reused in the same type of products.
- Cascade: this approach envisages component recovery, nevertheless, it is normally used in another, less demanding use (downgrading).

Manufacturing processes play a crucial role in putting in place the aforementioned strategies. Only a proper manufacturing technology innovation could enable the transition towards material efficiency practices. This aspect is highlighted by Tolio et al. (2017), they introduced the concept of demanufacturing integrated with remanufacturing as strategies enabling Circular economy. The authors state that “A sustainable transition to Circular Economy businesses will need to be supported by fundamental innovations, driven by the manufacturing industry, at systemic levels”. Manufacturing scientists are called to rethink and to find new manufacturing processes suitable for EoL metal components reprocessing. This is particularly true for Remanufacturing and Reshaping strategies. Remanufacturing has caught the attention of many researches over the past few years. Numerous studies on business model descriptions, production systems and processes level analyses have been published (Esmaeilian et al. 2016). Also, Remanufacturing normally refers to products rather than single components.

Concerning reshaping applied on End-of-Life metal-based components, very few researches are available in literature. Tilwankar et al. (2008) directly rerolled steel recovered from vessels into semi-finished products (plates, bars and rods used). They calculated that this process (ship breaking, transportation to mills, and then rerolling) allowed 60% of energy saving. Brosius et al. (2009) in a review paper refers to the possibility of converting a demounted automotive engine-hood into a rectangular sheet metal component by using sheet hydroforming process. Takano et al. (2008) applied Single Point Incremental Forming (SPIF) process to reform sheet characterized by non-uniform thickness. The reshaping approach involved the flattening of a previously bent sheet and a subsequent incremental forming step. Abu-Farha and Khraisheh (2008) proposed the use of superplastic sheet forming for applying reshaping strategies on magnesium-based components. Ingarao et. al. (2017) proposed an early theoretical model to explore the potential energy savings obtainable by reshaping approach implementation.

The aforementioned approaches are still preliminary and there is a research need in this domain, the potential of metal shaping processes as a reshaping medium hasn't yet been explored. Both technological and environmental performances are still to be analyzed. Sheet metal based components account for a quite large share of the global semi-finished production. In the case of aluminum alloys, sheets (including strips, foil production) account for about 45% of the yearly global demand (Allwood and Cullen, 2012). Therefore, finding out reuse options for sheet metal based EoL components would enable significant environmental impact reduction.

In this paper, the potential of flexible sheet metal forming processes for reshaping sheet metal based components is analyzed. To be more specific, SPIF as a reforming strategy is proposed. An experimental procedure made of deep drawing followed by SPIF process to replicate the reshaping is presented. SPIF is applied to change the shape of an AA-5754 aluminum alloy square box. The authors have recently analyzed the process mechanics as well as proved the technical feasibility of such an approach (Ingarao et al. 2020). Along with the technical feasibility of the process, the environmental performance of the reshaping approach is crucial to evaluate the potential of such an approach. The present paper, therefore, aims at outlining the environmental impact of the SPIF based reshaping approach; in this respect a Cumulative Energy Demand (CED) and CO<sub>2</sub>-eq. comparative analysis is presented. Three different routes are analyzed and compared to one another: SPIF based reshaping, conventional recycling and

SSR routes. Strengths and weaknesses of SPIF based reshaping approach are also discussed and the research needs to scale up this approach outlined.

## **2 Single point incremental forming as a process for reforming EoL components**

Reprocessing EoL components rises new challenges for manufacturing processes scientist. As a matter of fact, returned cores are characterized by high variability of quality conditions (Munot and Ibrahim 2013); such high variability coupled with the increased product variety results in a need of a high level of flexibility and reconfigurability of de- and remanufacturing processes/systems (Tolio et al. 2017). Also, reprocessing sheet metal based EoL components poses further technological issues. Returned components are normally characterized by high heterogeneity as there are localized thinning areas (caused by the original forming processes) while other areas of the component underwent lower deformation. In consequence, in the highly thinned zone, there is limited residual formability while in the less deformed zones it is still possible to apply a forming process to change the component shape.

In conclusion, the ideal candidate for reforming sheet metal based components must be a flexible process and it has to enable local forming action.

Single Point Incremental forming seems to perfectly meet the aforementioned requirements. In SPIF processes the part is formed in a stepwise manner incrementally by means of a generic tool stylus which is Computer Numerically Controlled. The sheet is clamped by the means of a non-work piece specific clamping system. This process is highly flexible as no dedicated tools are required but a simple universal tool is needed to apply the deformation in the sheet to get the desired geometry. The shape is given by the numerically controlled tool path. Also, local action of the SPIF process allows one to selectively form the part of the sheet characterized by suitable leftover deformation avoiding risk zone (such as the area with significant local thinning). SPIF provides a further advantage; in fact, the vast scientific literature on this process (Jeswiet et al. 2005; McAnulty et al. 2017) proved that SPIF enables the sheet formability to be significantly enhanced with respect to conventional stamping processes. Such enhancement in formability is caused by the low forming forces along with peculiar process mechanics (Duflo et al. 2018). The enhanced formability results in better performance with respect conventional stamping processes in re-forming (reshape) already formed components. In fact, EoL components are characterized by reduced formability as they already underwent an initial deformation to obtain the EoL final shape.

## **3 Material and methods**

The overall reshaping idea relies on the possibility to reuse a large amount of sheet metal based waste stream avoiding conventional recycling. Specifically, the proposed reshaping approach envisages to safely disassemble a large sheet metal component from End of Life products, such as automobile body, washing machines, etc. and to directly re-form the components by means of SPIF processes (figure 1 a). The new (reshaped) components can be, therefore, used either in the same sector of the EoL or allocated a different function.

In order to replicate such a reuse approach, the procedure as reported in figure 1b was adopted. In particular, after cutting a circular blank out of an aluminum sheet a deep drawing process was performed in order to replicate the first manufacturing process. Deep drawing is a very common process and its mechanics can be found in most sheet metal stamping processes of the automotive industry. The obtained square box will be from now on referred to as the EoL component. In figure 1b two different geometries are illustrated for the reshaped component with both a cone as well as a dome shape. To highlight the variety of forms possible utilizing the SPIF process.

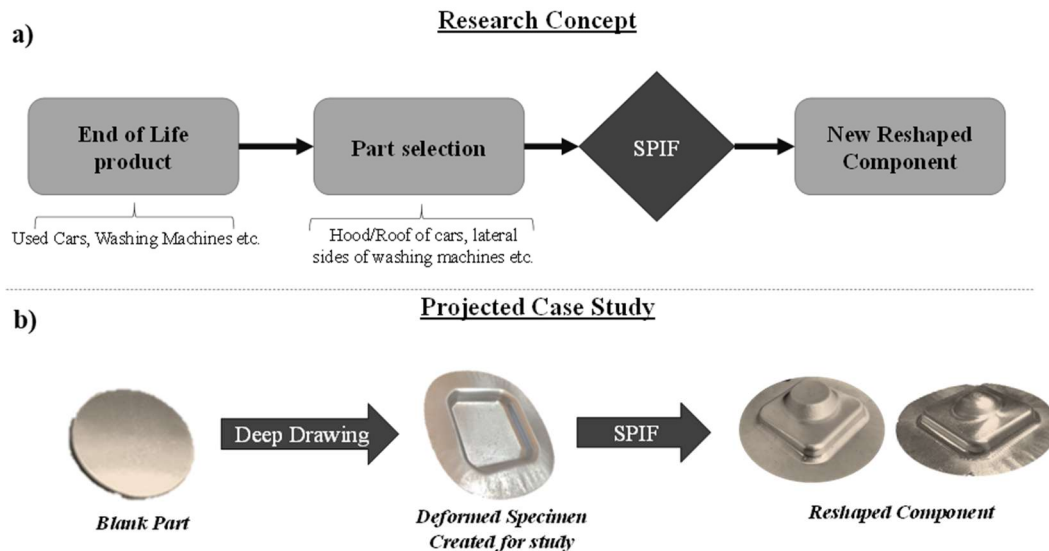


Fig. 1 a) Concept of the reshaping strategy; b) Approach utilized for research realization.

In figure 2 the selected geometries for developing the analysis are reported, Specifically, the EoL component (Fig. 2 a) and the reshaped part (Fig. 2 b with main dimensions is reported. Thinning distributions were acquired for both the EoL specimen and for the reshaped components. The samples were resin casted in an epoxy resin and later cut along the diagonal and examined through a microscope to obtain the thickness distribution of the part.

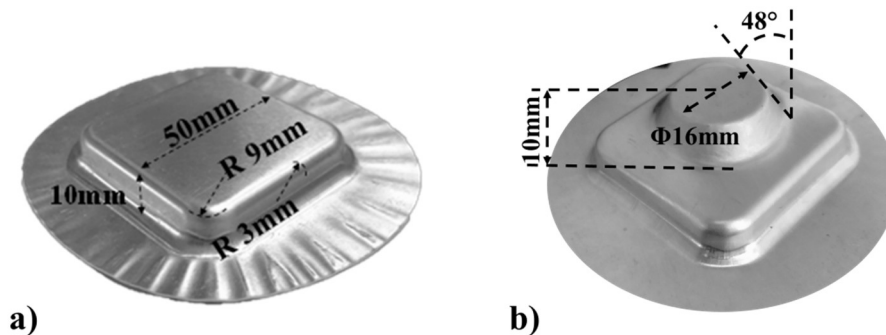


Fig. 2 Geometrical Parameters: a) End of Life component; b) New/Reshaped component.

It is worth mentioning that in DD processes, the thinning phenomenon (up to about 15% in the present case study) is basically concentrated at corners. The corners are, therefore, critical zones in terms of reshaping as they have limited formability. In order to actually replicate the reshaping process, the EoL Component is to be worked on further by the SPIF process. In order to verify the performance of the proposed approach, the SPIF process was applied to the base of the EoL components. Although the degree of deformation at the base of the square box is limited after the first DD operations, it is interesting to analyze to what extent the SPIF operations affect the highly thinned areas (with possibly limited formability) of the DD part. The previous work of the authors (Ingarao et al. 2020), proved some advantages of using SPIF for reshaping purposes. In fact, the local action of SPIF allows selectively reworking of safe areas of the EoL components. Also, the improved formability allows to superimpose further deformation even in already formed zones (such as the bottom corner of the DD component). In that paper, the authors proved that even in a lab-scale case study, the SPIF process affects the corners of the

EoL components. In fact, a further deformation/thinning occurs in the corner when SPIF operates nearby. Such an aspect makes the presented approach closer to realistic case studies.

Specifically, the flat base was changed by manufacturing a frustum of a cone with a base diameter of 34 mm and 10 mm depth. In this research the clamping system for performing SPIF, as shown in Figure 3, was set up on a 4 axes CNC milling machine, a tool with a high-speed steel based 4 mm diameter was used. A helical tool path with a 0.2 mm descent was applied for each spire; this choice was driven by the will to reduce the electric energy demand (which increases with decreasing the step down) while obtaining a satisfactory surface quality (which would decrease with increasing step down) (Ingarao et al. 2014).

Although the SPIF process causes severe thinning in the cone walls (35% in this specific case study), a sound sample was obtained as neither ductile fracture nor plastic instability phenomenon occurs (as in figure 2 b). It is worth mentioning that at this stage of this research line, the clamping system for the reshaping by SPIF is still an issue. Normally SPIF is carried out on a flat sheet and the clamping system is a sample metal framework applying vertical forces to hold the sheet. In the case of EoL components, in many cases, the lack of flat sheet may occur and therefore new clamping systems are to be identified. In this research, the leftover flange (intentionally left) from the deep drawing process was used as a flat sheet portion to apply the clamping system as depicted in figure 3.

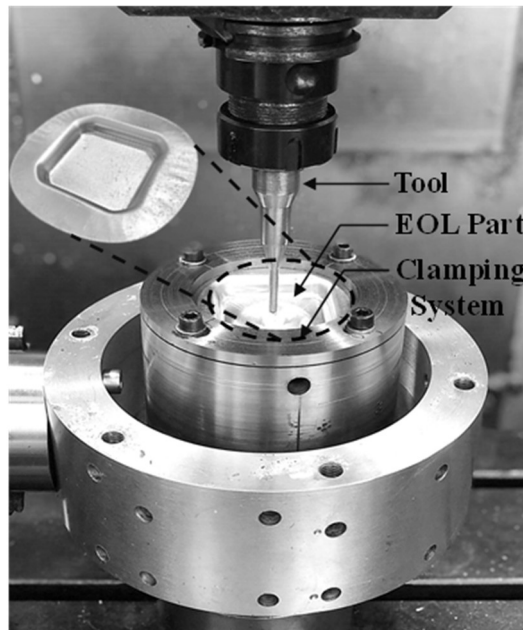


Fig.3 Experimental set up of SPIF process

#### 4 The comparative CED and CO<sub>2</sub>-eq analyses

In this section, the comparative analysis of three different EoL strategies for aluminum-based sheet metal components is presented. To be more specific, the performance of the here proposed SPIF reshaped approach is compared with those of two different recycling strategies: conventional and SSR based technique. For the latter approach, the ECAP extrusion-based process was selected as the most analyzed (Tekkaya et al. 2009). The aim of such comparison is to quantify the environmental performances of a new, here proposed, reuse strategy. Also, the study aims at identifying the main factors influencing comparative analysis results. In this section, after describing the system boundary and the main Life Cycle Inventory data, the discussion of the obtained results have been reported.

#### 4.1 System boundary and major assumptions

The functional unit selected for the comparative analysis is the reprocessing of one single component. For each strategy, all the process steps to turn an EoL component into the reshaped one are taken into due account. Concerning the metric for comparison, Cumulative Energy Demand (CED) (MJ) and CO<sub>2</sub>-eq emissions (Kg) were used. The adopted system boundary with all the steps included in the analysis is reported in figure 4.

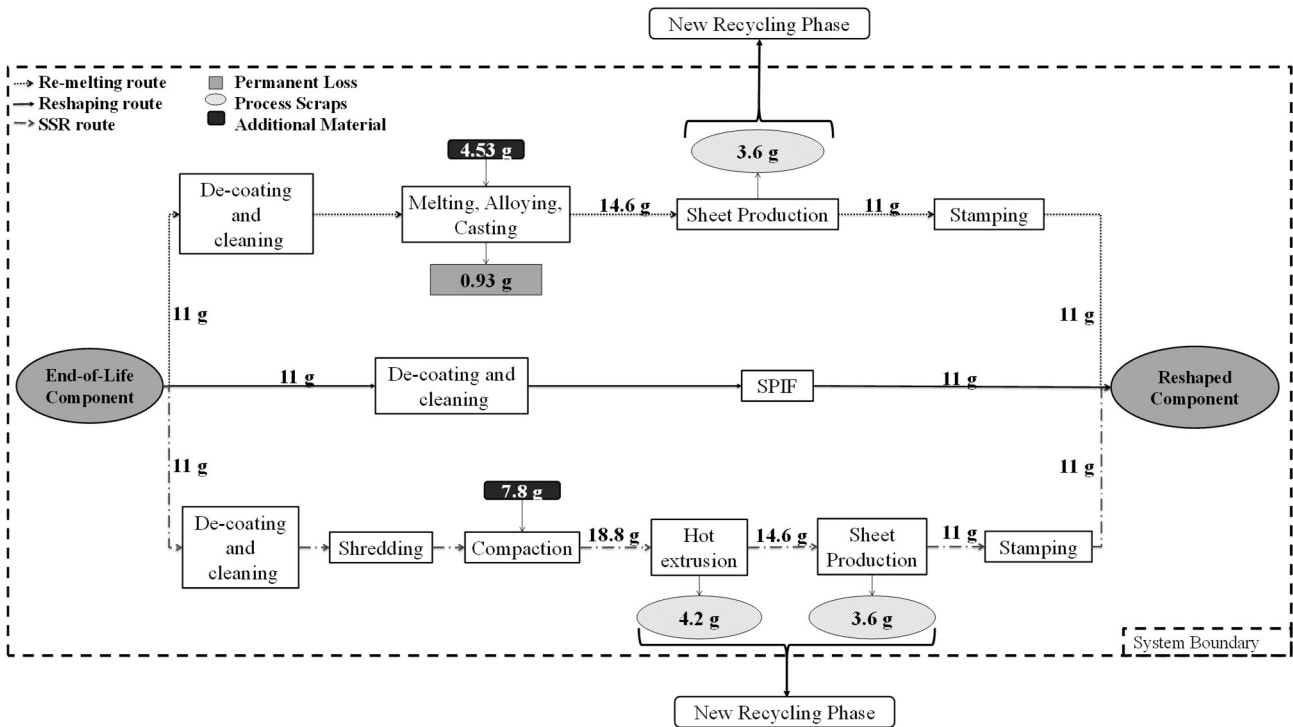


Fig. 4 System boundary with the process steps and the mass flow highlighted.

In the following paragraph some details about assumptions made to deal with electrical energy demand, material yield at different process steps as well as the material scraps are specified. Regarding process's electric energy demand, it was converted into primary energy source consumption by considering an average efficiency of 34% to account for the energy generation and the transmission losses. Also, to convert the electricity consumption into CO<sub>2</sub> emissions Carbon Emission Signature (CES) approach as suggested by Jeswiet and Kara 2008 was adopted. A CES coefficient equal to 0.447 (kg/kWh) was used considering the Italian electricity production mix.

A far as Material yield occurring during each process, both permanent losses as well as process scraps are modeled in the present study. It is worth mentioning that as the reshaped component is a sheet based one, a sheet production step is to be considered for both of the recycling routes, this step is mandatory to obtain a sheet metal to be stamped. Overall, it is possible to see how the reshaping process allows significant process steps reduction while involving less material. It is worth mentioning that for the SSR route both extrusion and sheet production processes (homogenization, hot-rolling, cold-rolling and annealing) have to be included. In fact, studies showed that extrusion is still necessary for a better consolidation also in the case of sheet production from scraps (Allwood et al. 2011 and Chiba et al. 2011).

Concerning the material scraps, two different kinds of material losses have been considered: processes scraps and permanent losses (occurring during melting because of oxidation).

Concerning processes scraps, these are basically home scraps (high quality with a high level of purity), according to the definitions of the EAA (2018), therefore they can be easily recycled. It was, therefore, assumed that such scraps leave the system without any environmental cost.

Concerning permanent material losses occurring during re-melting, these are much more damaging scraps from the environmental impact point of view. The related impact was dealt with by adding the same amount of primary aluminum in the model. As it can be observed, extra material was added at different levels for compensating the material losses (both permanent and process scraps). In the re-melting route, extra material was added at the melting level while in the SSR route it was assumed that extra material can be added in the compaction step.

## 4.2 Life Cycle Inventory

The life cycle inventory data was generated utilizing different approaches. Data found in scientific literature, databases and technical reports were used. Also, experimental measurements and modeling approaches were implemented to set up a reliable inventory data set. Overall, the EAA environmental report was considered as the primary reference as it provides reliable data for aluminum production and processing. Besides this, the CES Edupack database and the comparative analysis provided by Duflou et al. (2015) were also used as a data source. In table 1 all the data along with the used references for the LCI are reported. In the case of SPIF process, a research by Ingarao et al. (2014) was referred, which, after comparing the efficiency of three different set-ups able to perform SPIF processes, indicated that a robot-assisted SPIF was the most efficient, and thus chosen for the intended study. In that study, the authors provided a model able to link the Ultimate Tensile Stress of a given material being formed to the robot power demand while forming.

In the present study that model is used to quantify the electric energy demand of the SPIF based reshaping approach. Also, in that study (Ingarao et al 2014) the authors proved that forming time is the dominant factor for electric energy demand. Process parameters (feed rate and step down) are to be selected in order to get a forming time as little as possible. A higher machine feed rate (1500 mm/min) coupled with a high step-down value was considered as a best case scenario and a lower feed rate (500 mm/min) as a worst case scenario. These two variants were carried out with an intent to analyze the effect of wrong process parameters selection on the environmental performance of the reshaping. Although different feed rates can cause a difference in surface quality (Hamilton and Jeswiet, 2010), the above selected values led to a satisfactory surface (both internal and external surfaces) quality with no significant difference.

Since the stamping process was not carried out on an industrial press, a FEM code was used to simulate the stamping process and predict the punch load as a function of the distance traveled, thus the theoretical (plastic deformation energy plus the work needed to overcome the friction actions) forming work was calculated by quantifying the area under the force-time graph. The obtained value on dividing by the press efficiency, assumed as 0.25, resulting in the electrical energy consumption. An idle machine time of 20s was assumed for each working cycle during which average power consumption of 5kW was considered (Ingarao et al. 2016).

One of the main advantages of SPIF is that it doesn't require dedicated tools, such aspect makes this process more energy efficient with respect to conventional stamping when small batch sizes are to be manufactured. This aspect has been discussed by Cooper and Gutowski (2018). In the present study, the impact of the tooling for the stamping processes was taken into account. It is assumed that the tooling is made of O1 steel according to the ASME guidelines (Semiatin S. L. 1993), the energy and the CO<sub>2</sub>-eq. emission related to material production and processing were quantified by using Eco-properties found in CES Edupack (Granta Design Limited 2017). Material impact for tooling is the dominant factor and therefore its modeling deserves particular attention. Specifically, it is necessary to account for the credits arising from recycling. Although there is not one single criterion to account for recycling benefits, some useful guidelines are provided by Hammond and Jones (2010). Overall, double counting should be avoided, either it has to be considered the fraction of the recycled material in the input material (workpiece to be worked) or it has to be considered the amount of material that will be recycled at the component EoL stage. Two principal methods exist: (1) the recycling content approach and (2) the substitution method. The first one ascribes the full benefit of material recycling to the start of its life, lowering the material impact by considering the fraction of recycled material in the input

material (R). The substitution method, instead, allocates the environmental credit of recycling to the end-of-life stage. In this case recovery and recycling rate as well as material recycling yield (r) of the recycling processes for the considered material is to be considered. Normally the r value is higher than R making the substitution method often an optimistic estimation. Equation (1) and (2) can be used for accounting for material impact with the recycling content and the Substitution method, respectively. For CO<sub>2</sub>-eq. equations 1 and 2 can be applied accordingly.

$$E_{\text{Recycling content approach}} = E_V \cdot (1-R) + R \cdot E_R \quad (1)$$

$$E_{\text{Substitution method}} = E_V - r \cdot (E_V - E_R) \quad (2)$$

where:

R=recycled content (fraction of recycled material in the input material);

r=recyclability (fraction of material recycled at the end-of-life);

E<sub>R</sub>=embodied primary energy, secondary production;

E<sub>V</sub>=embodied primary energy, primary production.

For the present analysis we took R value as 55% (Granta Design Limited 2017) and r value as 90% (Mayyas et al. 2012).

Table 1. Life cycle inventory data

Process	Primary energy (MJ/kg)	CO <sub>2</sub> eq. emission (kg)	Yield	Reference
De-coating & Cleaning	2.30	0.100	1	Swanson 2005
AA-5754 Primary production	210	13.3	--	Granta Design Limited 2017
O1 steel Primary production	41.45	2.76	--	Granta Design Limited 2017
O1 steel Secondary production	10.3	0.81	--	Granta Design Limited 2017
Shredding	0.60	0.105	1	Mayyas 2012
Compaction	8.79	0.370	1	Duflou et al. 2015
Hot Extrusion	16.0	0.680	0.77	EAA environmental report 2018
Extra Pressing Energy	2.05	0.090	--	
Sheet Production	9.00	0.430	0.75	Duflou et al. 2015
Melting & Casting	5.90	0.330	0.88	EAA, environmental report 2018
				EAA, environmental report 2018
Stamping (Per Part)	0.025	0.001	1.00	Calculated
SPIF - Worst Case Scenario (Per Part)	0.67	0.028	1.00	Calculated
SPIF - Best Case Scenario (Per Part)	0.36	0.015	1.00	Calculated

### 4.3 Discussion of the results

In this section the results of the developed analyses are reported for both Cumulative Energy Demand and CO<sub>2</sub>-eq. emissions. The results are discussed with the aim to analyze the influence of the factors: 1/the batch size, 2/ the methods used for recycling credits accounting and 3/ the used feed rate in SPIF. The results for CED with varying batch sizes are reported in figure 5a for the case of the substitution method and recycled content. Overall, as the tooling is the only varying factor with changing batch size, the decreasing trend is visible only for the conventional

and the SSR based approaches. Whereas the reshaping approach has a constant trend and its value significantly decreases when using a higher feed rate. It can be seen that SPIF based approach, with a higher feed rate (Reshaping HFR), has the lowest CED even when very high batch sizes are considered; the SPIF based approach is always the best solution regardless of the analyzed scenario. Whereas, when SPIF with Lower Feed Rate (Reshaping LFR) is considered, break-even points (where two routes demand the same amount of CED/CO<sub>2</sub>-eq.) occur: under the recycled content approach, BP occurs only between the Re-melting route and Reshaping LFR at a batch size of 319. When the Substitution Method approach is considered, break-even points occur at much lower batch size values, i.e. 187 for the re-melting route with Reshaping LFR, and at 638 between SSR and Reshaping LFR. This change in CED values is due to the lower environmental impact ascribed to the material by the substitution method as discussed in the previous section. Similarly, for calculations regarding the CO<sub>2</sub>-eq. (Figure 5b) break-even points occur just between the Re-melting and the Reshaping LFR routes, at a batch size of 630 when calculations were done using the recycled content approach and at 397 on using the substitution approach.

The results prove that the proposed Reshaping approach has the potential for putting in place environmentally friendly material reuse strategies. As a matter of fact, when lower feed rates are considered, BP are identified and Reshaping by SPIF outperforms other strategies for selected batch size. Better yet, when the proper SPIF process parameters are selected (Higher Feed Rate) reshaping proved to be the best option both in terms of CO<sub>2</sub>-eq. emissions and CED regardless of the analyzed scenario (even for large batch size).

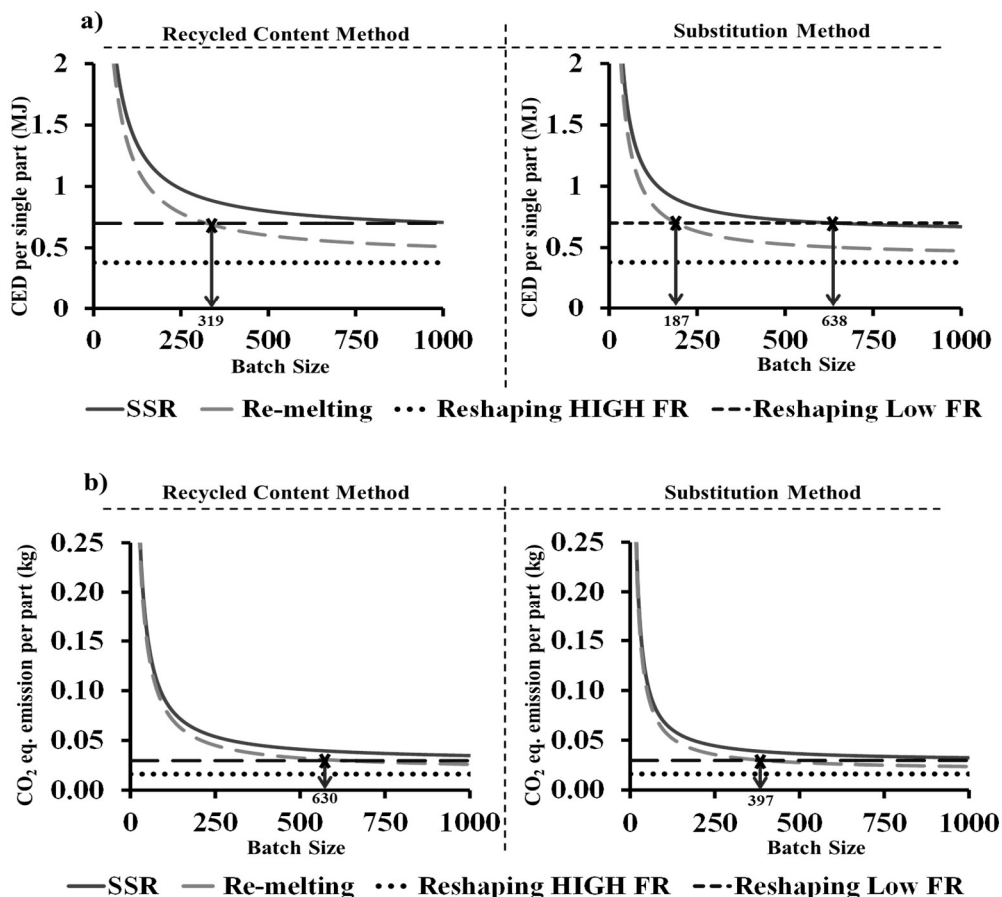


Fig. 5 Routes performance trends for recycled content and substitution approaches with varying batch size: (a) CED trend (b) CO<sub>2</sub>-eq. emission trend.

Unlike what was reported in an earlier study (Dufloy et al. 2015, Baffari et al. 2019), the SSR approach displays worse performance than Re-melting based route. This is mainly due to the higher number of process steps as both extrusion and sheet production steps have been included. Also, considering the scraps morphology, a small value of permanent losses (6%) are

considered as suggested by Duflou et al. (2015). In order to provide a clearer picture, the breakdown analysis for each analyzed route is reported in figure 6. In this figure the contribution of each factor towards the total CED and CO<sub>2</sub>-eq emission for a batch size of 350 is illustrated. As far as SSR is concerned, besides tooling contribution, it is badly affected by the larger number of high energy demanding processes steps (compacting, hot extrusion and sheet production). Concerning re-melting, the high contribution of permanent loss is evident as it accounts for 27% and 32% of the total for recycled content and substitution method scenario, respectively. Finally, for SPIF it is possible to see that the electric energy demand while processing is the dominant factor and it is significantly affected by the process times. Proportional values with similar trends were obtained for CO<sub>2</sub>-eq. emissions, results are reported in figure 6 b.

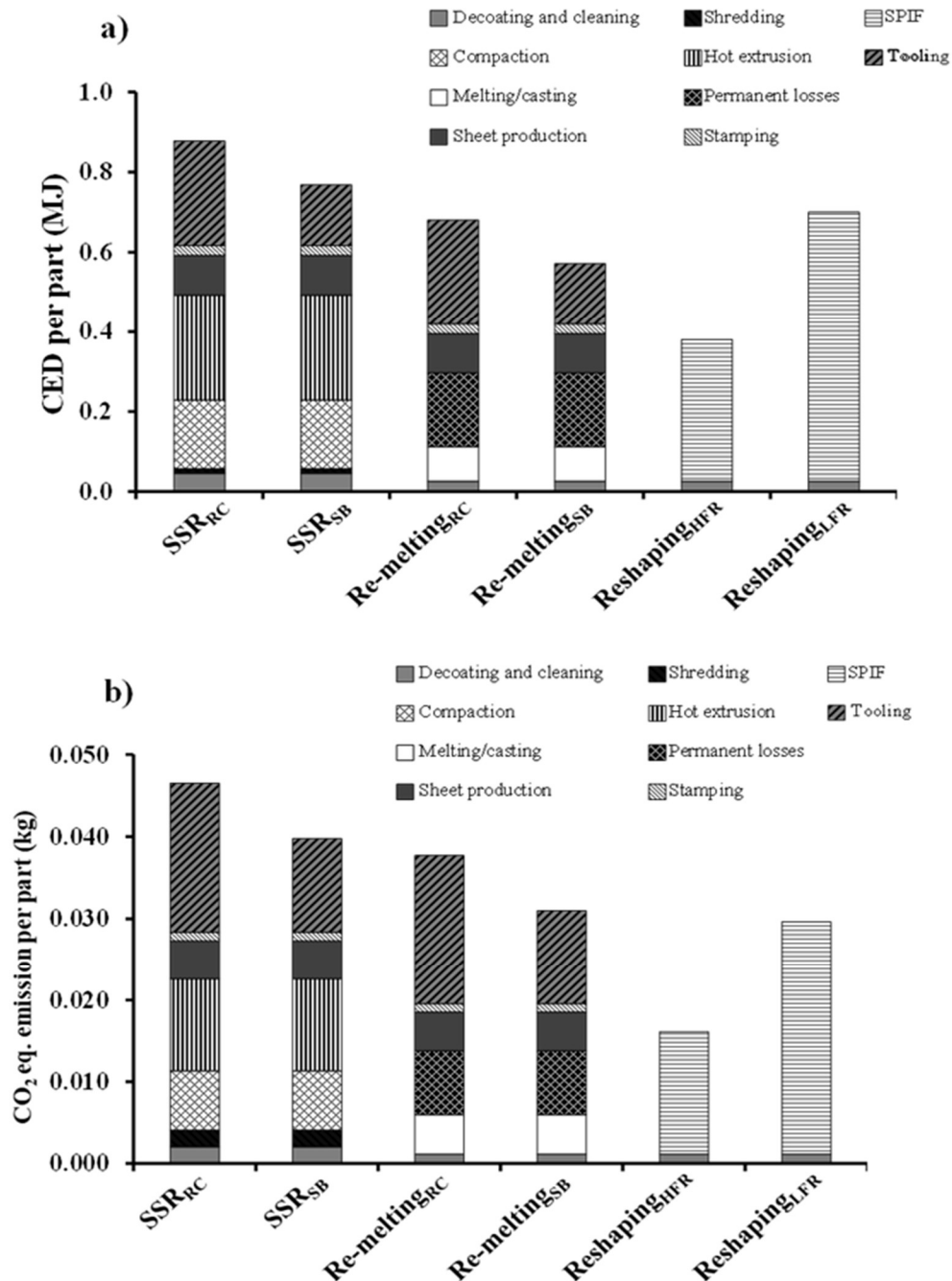


Fig 6. Process steps contribution of the considered approaches for a batch size of 350 parts: (a) CED shares per part; (b) CO<sub>2</sub> eq. emission per part.

## 5 Conclusions and outlook

In this paper, a novel reuse strategy for sheet metal based components is presented. The suitability of Single Point Incremental Forming process in changing the shape of EoL components has been proved.

By means of an experimental campaign, the technical feasibility of aluminum alloys sheet components is presented. In particular, SPIF process was applied to change the shape of a square box previously obtained by deep-drawing processes.

The EoL components have been changed in shape successfully and defect-free new/reshaped components were obtained. It has been proved that the local action and the high flexibility nature of SPIF as well as its enhanced formability in sheet forming processes, perfectly meet the requirements of sheet metal based EoL components. Besides the technical feasibility of the novel reshaping approach, the paper aimed at analyzing its environmental impact performance. In this respect, a comparative analysis with two other strategies, namely conventional recycling and ECAP based SSR approaches. Different scenarios were considered with varying the production batch size and the method for accounting for credits arising from recycling.

The SPIF based approach, subjected to proper process parameters selection, proved to be the most environmentally friendly strategy regardless of the analyzed scenario. For instance, for a batch size of 350 parts, the reshaping approach allows and CO<sub>2</sub>-eq. emissions saving as high as 47% and 50% with respect conventional and SSR approaches, when the Substitution method is considered, respectively. When the analysis is developed with the Recycled Content approach the saving increased up to 57% and 59%, respectively. The advantage is mainly due to the fewer steps as well as to the less material (less material scraps) involved in turning EoL parts in a new/reshaped component.

Besides the benefits just reported, some issues are still to be addressed to scale up such a new reshaping processes; some of them are discussed below.

1/Similarly to what happens for remanufacturing processes, poor information about return products make the inspection step fundamental for making reuse strategies successfully from technological, economic and environmental perspectives (Errington and Childe, 2013). For sheet metal based EoL components, the thinning distribution is a crucial piece of information to properly design the reshaping process. Since the thinning distribution is caused by the first forming processes, this information can be easily accessed if the company who develops reshaping is the original equipment manufacturer, otherwise a proper inspection step is to be envisaged. Possible candidates for the inspection step may be laser-based or ultrasound, the suitability of the inspection technology is to be still identified and both technological and environmental performance have to be considered. In this paper, no energy was ascribed to the inspection step because of the lack of industrial practices.

2/Another step deserving research attention is the de-coating. Normally, sheet metal based components have an outer layer, typically painting, to be removed. Such layer has to be removed without affecting the mechanical properties of the components. These processes normally take place at elevated temperatures, and the effect of the sheet heating on the mechanical properties it is mandatory to identify proper de-coating strategies.

3/A research effort is still needed for designing an adaptive and effective clamping system. The clamping system should be easily adaptable to changeable workpieces (both in shape and dimensions). Also, the flange is not normally available in EoL life components and, therefore, an innovative clamping system for SPIF should be provided not relying on flat sheet availability.

4/ It is worth remarking that, although SPIF perfectly meets the requirements for reshaping, it has some intrinsic issues such as high cycle time, poor accuracy which could still limit the reshaping implementation at the industrial level. In this respect, other flexible sheet metal forming processes could be considered for reshaping purposes. For instance, other candidates could be: Hydroforming (possibly the assisted temperature versions) and Super Plastic Forming. These options deserved to be explored to identify the most suitable process with varying EoL properties.

Besides the above mentioned technical issues, other aspects have to be dealt for actually putting in place the here proposed reshaping technology. Specifically, proper reverse logistics have to be identified as the recovery step is of crucial importance to get suitable cores to be remanufactured. Finally, a proper business model making the SPIF reshaping approach both environmentally friendly and profitable for manufacturing companies should be pointed out.

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