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An energy efficiency analysis of Single Point Incremental Forming as an Approach for Sheet Metal Based Component Reuse

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ABSTRACT

Producing materials causes about 25% of all anthropogenic CO_2 emissions. Metals play a significant role, steel and aluminum account for 24% and 3% of worldwide material related emissions respectively. Fostering resources efficiency strategies in the field of sheet components could lead to a significant environmental impact reduction. Reshaping could be one of the most efficient strategy to foster material reuse and lower the environmental impact due to material production. Specifically, for aluminum recycling, the overall energy efficiency of conventional route is very low and, more importantly, permanent material losses occur during re-melting because of oxidation.

The present paper aims at presenting the technical feasibility of Single Point Incremental Forming (SPIF)-based reshaping approach. Change in shape of aluminum stamped part is obtained through SPIF process implementation. Preliminary energy savings quantification through life cycle energy and material flows modelling are provided, energy efficiency of conventional recycling approach and SPIF-based reshaping routes are analyzed and compared.

1. Introduction

Making materials consumes about 21% of the global energy demand, and causes about 25% of the global CO_2 emissions (Worrell et al., 2016). Looking at the energy breakdown analysis it is possible to notice that such an environmental burden is dominated by only five materials: steel (25%), cement (19%), plastics (5%), paper (4%) and aluminum alloys (3%) (Gutowski et al., 2013b). The raw material demand is to be reduced and strategies to use less material as well as to keep as much material as possible in the circle is, by now, mandatory.

Longer life, more intense use, repair, product upgrades, modularity, remanufacturing, component re-use and open/closed loop recycling are some of the strategies to put in place to reduce the environmental impact of raw material production (Tolio et al., 2017). Regarding metals, recycling is the most applied strategy (Atherton, 2007), as a large number of metals can be recycled repeatedly at high rates. As far as lightweight materials are concerned, primary energy savings as high as about 90% can be obtained for aluminum, magnesium and titanium alloy (Ingarao et al., 2017). Despite that, there is still room for making recycling processes more efficient and less resource demanding. Regarding aluminum alloys, conventional recycling routes are based on re-melting. This process is not efficient in terms of energy demand and permanent material loss occurs. Concerning energy intensity, it is worth remarking that the theoretical energy to melt and cast aluminum scraps is 1.14 MJ/kg, the actual average overall energy consumed for recycling aluminum in the EU is 5.59 MJ/kg. Also, the high affinity of aluminum to oxygen can lead to permanent material losses during re-melting due to oxidation. Replacing permanent losses with primary aluminum significantly increases the embodied energy of recycled aluminum (Duflou et al., 2015). There is a pressing need to put in place all the circular economy strategies to actually move towards a material efficiency transition.

Cooper and Allwood (Cooper and Allwood, 2012) presented a reuse framework for metals products/components. In this research the authors identified four main reuse strategies: Remanufacture, Reshape (applying metal shaping to obtain a new geometry), Relocate (relocating envisages recovering component and applying little refurbishment to apply it in the same type of products) and Cascade (recovering component and use it in an another less demanding use).

Manufacturing scientist have to make a research effort addressed to find proper manufacturing processes enabling the aforementioned strategies. This is particularly true for Remanufacturing

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and Reshaping strategies. It is worth mentioning that remanufacturing has caught the attention of scientists over the last years, as a matter of fact plenty of research can be found from the business model description up to production system and process level analyses (Esmaeilian et al., 2016).

Concerning reshaping applied on End-of-Life (EoL) metal based components, very few researches are available in literature.

Tilwankar et al. (Tilwankar et al., 2008) directly rerolled steel recovered from vessels into semi-finished products (plates, bars and rods used). Brosius et al. (Brosius et al., 2009) turned a demounted automotive engine-hood into a rectangular sheet metal component by using sheet hydroforming process.

Takano et al. (Takano et al., 2008) applied incremental forming process to reform sheet characterized by non-uniform thickness. The reshaping approach includes the flattening of a previously bent sheet and a subsequent incremental forming step.

Abu-Farha and Khraisheh (Abu-Farha and Khraisheh, 2008) proposed the use of super plastic sheet forming for applying reshaping strategies for magnesium based components. Ingarao et. al. (Ingarao et al., 2017) proposed an early theoretical model to explore the potential energy savings obtainable by reshaping approach implementation.

Within the domain of sheet metal based components, the main idea concerns the possibility to take advantage of both flexibility and enhanced material formability provided by the innovative and flexible incremental forming process. In fact Single Point Incremental Forming (SPIF)process is made of a simple tool moving according a spires based toolpath, therefore locally as well as incrementally formed. The shape is uniquely provided by the tool path and no dedicated tool are required.

Indeed, this local and incremental nature of SPIF process perfectly fits the features of the returned EoL components, as these components are characterized by inhomogeneous thinning and reduced formability as compared to original, unformed, flat sheet. Besides proving the technical feasibility of such an approach, the paper aims at outlining the energy efficiency of the SPIF based reshaping approach; in this respect a comparative primary energy analysis is presented. Specifically, the primary energy demand of the entire reshaping route is compared to the conventional (remelting based) route. Also issue to be still addressed for actual reshaping scaling up are also discussed.

Nomenclature

EoL End-of-Life
SPIF Single Point Incremental Forming

2. Materials and Methods

In this paper the suitability of using SPIF as reshaping process for sheet metal based components is analyzed.

After Single Point incremental forming process presentation in 2005 at CIRP (Jeswiet et al., 2005) general assembly, a large number of laboratories worldwide focused on this forming technology. Over the last 15 years the process has been analyzed under different perspectives (14).

SPIF is the most flexible sheet metal part manufacturing process. In fact, no tooling is required to get the desired geometry. Basically, the part is formed in a stepwise manner incrementally by means of a generic tool stylus which is Computer Numerically Controlled. The sheets are clamped by the means of a non-workpiece-specific clamping system and in the absence of a partial or full die.

It is worth highlighting that the local and incremental nature of SPIF process, causes very low forming forces especially when compared to those occurring during conventional sheet stamping processes. This phenomenon, coupled with the peculiar process mechanics (Duflou et al., 2018), enables the sheet formability to be significantly enhanced. For the purpose of the present paper, an

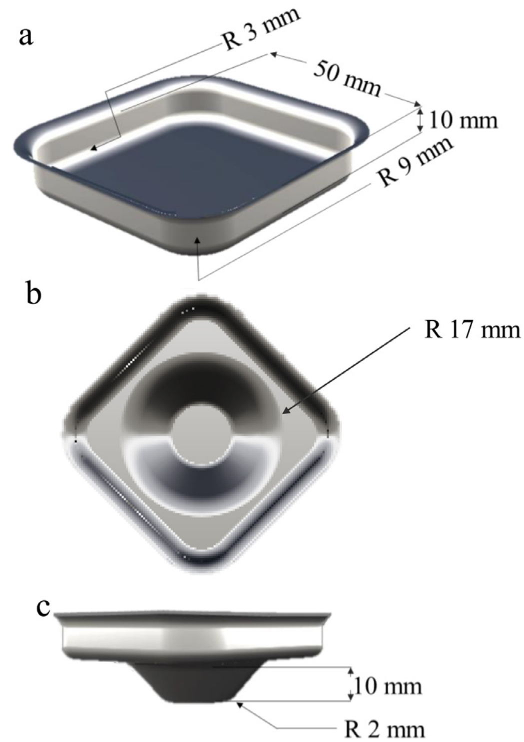

Fig. 1. (a) End-of-Life component; (b) Reshaped Component - Top view; (c) Reshaped Component- Side view.

enhanced formability means the possibility to re-form (reshape) already formed components. SPIF, therefore, provides the possibility to reshape EoL components characterized by reduced formability as they already underwent a first deformation to obtain the EoL final shape. Also, it is worth mentioning that EoL components are characterized by high diversity across the entire part; In fact, sheet metal based components are normally characterized by localized thinning areas while large part of the component has limited deformation. The local action of the SPIF process allows to selectively form the part of the sheet characterized by suitable left over deformation avoiding risk zone (such as the area with significant local thinning).

2.1. The analyzed case study

The selected case study was focused on studying the material reusability, by reshaping a square cup through SPIF process. The main idea was to consider the square cup as a returned End-of-Life aluminum based component. To justify the suitability of SPIF as an excellent reshaping alternative, the shape of an inverted frustum of a cone was imparted to the base of the cup. Geometrical details of the end of life square cup and of the reshaped one are depicted in Fig. 1. For the experimental analysis Aluminum alloys sheets (AA5754 H22) with a thickness of 0.5 mm were selected. Circular blanks 100 mm in diameter were cut out and considered as starting blank for the deep drawing process.

As shown in Fig. 1 (a) a square box 10 mm deep was obtained using grease to attain the ideal friction conditions between the blank and the tools, Fig. 1 (b) and 1 (c) illustrate the different views of the reshaped part geometry. In order to better describe the thinning distribution of the EoL part, the results of the numerical simulation of the deep drawing process is reported in Fig. 2. The thinning zones placed at the angles of the square box are visible.

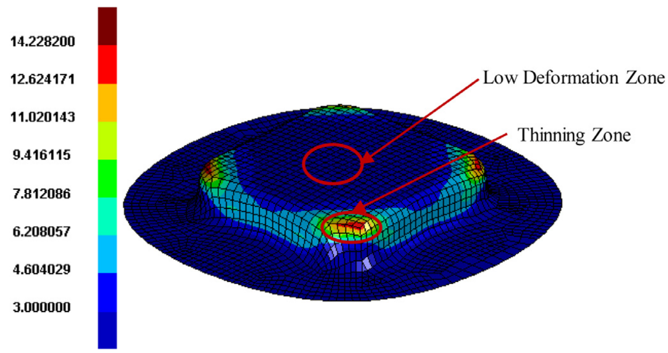

Fig. 2. Thinning distribution of the EoL component.

Fig. 3. Experimental set up of SPIF process.

Fig. 4. Reshaped/New component.

After this, the deformed sheet was worked on further with the SPIF process to attain the form of an inverted frustum of a cone with a base diameter of 34 mm and 10 mm depth, using a tool with a 4 mm diameter. The SPIF process was performed on a 4 axes CNC milling machine. A high speed steel based tool with an hemispherical form with a 4 mm diameter was utilized. A helical tool path was applied; a 0.2 mm descent was applied for each spire. The machinery and the clamping system along with the tool and the end-of life component are depicted in Fig. 3.

The final/reshaped component is reported in Fig. 4, as it can be seen the final component is defect free as neither fracture nor wrinkling phenomena occur. In order to better analyze the quality of the final component the thickness distribution of the obtained reshaped component was also analyzed. The product was, therefore, 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. A proper thickness distribution with a maximum thinning equal to 35% was observed. The maximum thinning value reveals that a significant amount of deformation can

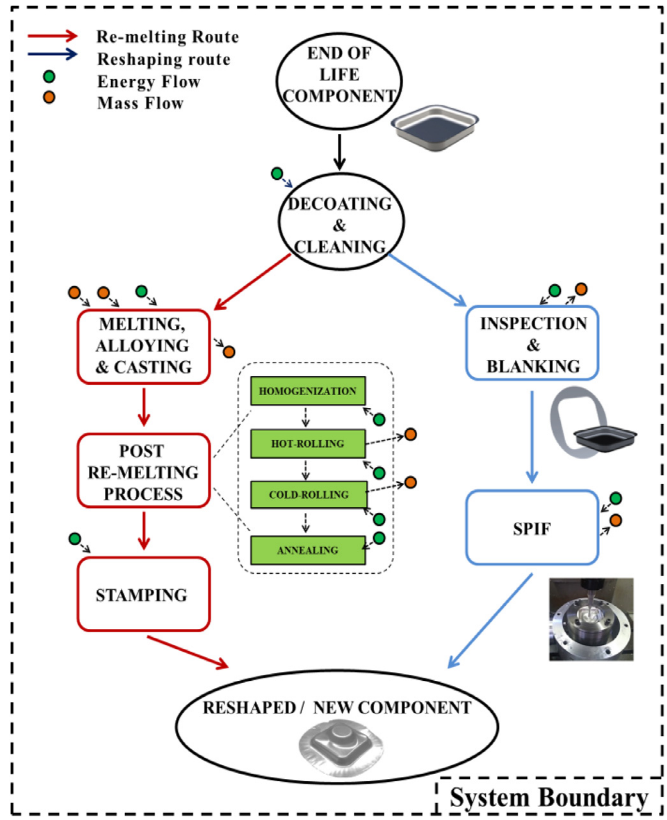

Fig. 5. System Boundary with considered process and material steps highlighted.

be achieved in the reshaping step without affecting the already deformed areas of the EoL part.

It is worth mentioning that at this stage of this research line, the clamping system for the reshaping is still an issue. As in many cases, a lack of flange can be a limitation in part's mounting for the reshaping step. In this research the artifice of not to cut the left over flange from the deep drawing process was used. The traditional clamping system for SPIF was, therefore, used for the reshaping step.

3. Primary energy comparative analysis

In order to evaluate the efficiency of the proposed approach a comparative analysis with the conventional re-melting route was done. The primary energy demand of both the approaches has been, therefore, modeled. All the material and energy flows to get the final desired component were taken into due account. For each step the processing energy demand (both electric and thermal) together with the material yield were considered.

3.1. System boundary and major assumptions

The analyzed system boundary, with all the included processes along with detailed material flow, is depicted in Fig. 5. The functional unit for developing the comparison is the manufacturing of one single product; the entire route from EoL component to Reshaped/New component was taken into account as well as for the re-melting route.

In order to compensate process scraps, addition of extra material is considered in the model. Concerning the re-melting route, as permanent material losses occur because of oxidation, and addition of primary aluminum was included in the model, instead.

It is worth mentioning that environmental impact of stamping step is affected by the tools manufacturing, and such impact should be ascribed to each single stamped part. In this research this impact was left out of as a large batch size was assumed making this contribution negligible when allocating it to a single part (16).

3.2. Life cycle inventory (mention where materials and energy details were taken from)

The main sources for the life cycle inventory are: 1/ the EAA environmental report (EAA 2018); 2/ the paper form Milford et al. 2011 where energy demands and material yields of several sheet metal processes are reported (Milford et al., 2011) and 3/ the CES Edupack database (EAA 2017).

As far as the electric energy of SPIF and stamping are concerned, two different strategies were implemented. Concerning the electric energy of stamping process, because of the lack of industrial press and production practices, the approach as proposed by Ingarao et al. (16) was considered. To be more specific, the theoretical forming (sum of the plastic deformation energy plus the work needed to overcome the friction actions) work (W) was first calculated. The FEM code was used to get a reliable prediction of the punch load as function of its stroke, the W value was, therefore, obtained by quantifying the area underneath such a curve. Then, to obtain the electrical consumption of the pressing step, W has to be divided by the efficiency of the hydraulic press, a value of 0.25 was assumed. As far as the energy consumption during the non-productive times is concerned, an idle time of 20 s was assumed for each working cycle. During the idle time, an average constant power absorption of 5 kW was considered.

Concerning the SPIF process, the study developed by Ingarao et al. (Ingarao et al., 2014) was used as reference. In this paper a comprehensive electric energy characterization of different SPIF platform is presented. As the robot proved to be the most efficient solution, the electric energy demand of this set-up (instead of the CNC milling machine actually used for performing the reshaping experiment) was considered for the present research. The power demand values of both productive and idle production modes as reported by Ingarao et. al. (Ingarao et al., 2014) were considered in the present analysis, the process parameters setting leading to minimum electrical energy consumption (high feed rate along with high step-down value) was used as a best case scenario, a worst case scenario in which a low feed rate of the robot was taken into account as well. This choice was driven by the will to analyze the effect of a wrong (non-environmentally friendly conscious) process parameter selection on the SPIF Reshaping primary energy demand.

For the addition of new Aluminum due to permanent losses, occurring in the Re-melting route, a primary energy value as high as 210 MJ per kilogram was considered, and to account for process scraps (which can be recovered and recycled) the substitution method was used for including the credits arising from recycling (EAA 2017). For all the processes, the electric energy demand was converted into primary energy source consumption by considering an average efficiency of 34% to account for the energy generation and the transmission losses. In table 1 the considered Primary energy values along with material yields are reported for each process step.

3.3. Results Discussion

The primary energy demands for the two analyzed routes are reported in Fig. 6a and the total energy consumption shares have been illustrated in the Fig. 6b. As it can be observed the reshaping route could enable an energy saving as high as 27% if the best case scenario (low forming time) is considered.

Table 1
Life Cycle Inventory data.

Process	Primary energy	Yield
De-coating & Cleaning (MJ/Kg)	2.3	1
Melting & Casting (MJ/Kg)	5.9	0.88
Homogenization (MJ/Kg)Hot Rolling (MJ/Kg)Cold Rolling (MJ/Kg)Annealing (MJ/Kg)Stamping (MJ/Part)SPIF–Worst Case Scenario (MJ/Part)SPIF–Best Case Scenario (MJ/Part)	1.41.851.31.20.0250.5680.355	10.90.9510.70.80.8

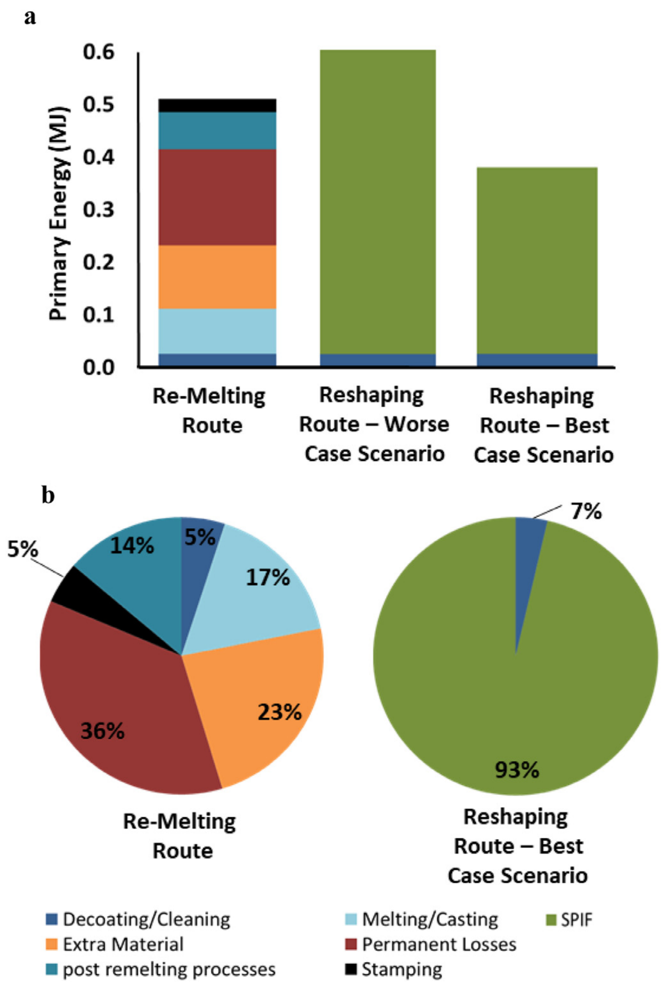

Fig. 6. (a) Primary Energy consumption comparative results; (b) shares of Energy consumptions.

On the contrary if the worst case scenario (high forming time) is considered the energy demand of SPIF increases significantly consequently the re-melting route becomes the more efficient approach.

It is interesting to notice that the bad performance of the conventional re-melting route is mainly due to higher amount of involved material, In fact, both permanent losses and extra material (to be included because of process scraps) account for almost 60 % of the total primary energy demand. Whereas in the case of reshaping route a higher machine feed rate plays an important role in rendering the process into a comparatively efficient one. Summing up, a higher number of process steps along with permanent material losses and process scraps render conventional practices inefficient and not environmentally friendly. On the other hand, although the SPIF reshaping route is the approach to be preferred, an energy conscious process selection is recommended. Also, it is worth mentioning that the environmental impact of the tooling was not taken into account in the present analysis. This factor can be crucial when small batch size are to be manufactured as the conventional route performance can be worsened significantly.

4. Conclusions and outlook

In this paper the technical feasibility of sheet metal components reuse by SPIF reshaping is proved. Also, the energy efficiency of this new approach with respect conventional recycling is quantified through a comparative analysis. A square cup was assumed as EoL component and a cone shape at the bottom of it was carried out by means of SPIF. The approach proved to be successfully as the new shape was obtained without fracture occurrence.

Results of the comparative analyses revealed that such a reshaping approach could lower the primary energy demand by 26%. Such a relevant saving is mainly due to less material involved. In fact, the conventional route is characterized by permanent losses due to oxidation as well as material scrap occurring in the several processes needed to turn melted aluminium into usable sheet.

Despite the abovementioned advantages, the road to make the reshaping approach applicable at industrial scale is still long. Some of the main issues to be still addressed follow:

1 Similarly to what happens for remanufacturing processes, the inspection step is fundamental for making reuse strategies successful. In this paper visual inspection is assumed and, therefore, no energy was ascribed to this step. It is worth mentioning that if the company who develops reshaping is the original equipment manufacturer, the knowledge on the thinning distribution may be available and a visual inspection could be satisfactory. On the contrary, if the "re-shaper" is an independent remanufacturers (reshaping other people's goods without license or support for direct sales into the aftermarket), the knowledge of thickness distribution of the EoL component is crucial for the SPIF based reshaping process design. In this respect, a proper inspection technology should be identified. Possible candidates, such as laser based or ultrasound, should be considered checking also the energy efficiency.
2 Proper de-coating step should be identified. When necessary, it has to remove the outer layer without affecting the physical properties of the material. Also. any thermal effect on the mechanical properties of the EoL should be taken into account in this process step.
3 An adaptive and effective clamping system should be designed. As a matter of fact, often flange is not available to clamp the EoL component. Unlike conventional sheet metal forming process where the input work-piece is a brand new flat sheet.

Besides the above mentioned technical issues to be still addressed, other aspects have to also be analyzed. Logistics solution and proper business models have to be identified, for proper component recovery and identification and for making also the approach profitable for manufacturing companies.

CRediT authorship contribution statement

Giuseppe Ingarao: Data curation, Conceptualization, Methodology, Writing - original draft. **Omer Zaheer:** Investigation, Writing - review & editing. **Davide Campanella:** Investigation, Writing - review & editing. **Rosa Di Lorenzo:** Supervision, Writing - review & editing. **Livan Fratini:** Resources, Supervision, Conceptualization.

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