17th International Conference on Sheet Metal, SHEMET17

An exploratory study for analyzing the energy savings obtainable by reshaping processes of sheet metal based components

Giuseppe Ingarao[a]*, Rosa Di Lorenzo[a], Livan Fratini[a]

[a]Department of Industrial and digital innovation, University of Palrtmo, Viale delle Scienze Ed. 8, Palermo 90128, Italy.

Abstract

Producing materials causes about 25% of all anthropogenic CO_2 emissions. Reshaping could be one of the most efficient strategy to foster material reuse and lower the environmental impact due to material production. Sheet metal forming processes can be applied to reshape sheet metal based component. This research field is still almost unexplored and the actual environmental impact saving potential has not been quantified. The present paper aims at starting to cover this research gap, a modeling effort to quantify the environmental impact saving of reshaping is proposed. Primary energy demand for conventional recycling and reshaping are quantified and compared. Primary energy savings obtainable for an aluminum hood reshaping for different production scenarios are quantified. Results reveals that reshaping could lead to significant energy saving with respect to conventional recycling route based on remelting. The present research is a first step to explore advantages and disadvantages of reshaping processes and to understand actual applicability of such a material reuse approach.

1. Introduction

Material production is responsible for a significant share of the greenhouse gas emissions. Producing materials causes about 25% of all anthropogenic CO_2 emissions [1]. Metals play a significant role, steel and aluminum account for 24% and 3% of worldwide industrial emissions respectively [2]. Minimizing material usage is, therefore,

---

* Corresponding author. Tel.: 3909123861847
  E-mail address: giuseppe.ingarao@unipa.it

mandatory for reducing the global emissions. Putting in place all the suitable material reuse strategies would enable metals primary production demand to be reduced. It is worth pointing out that aluminum sheet based components (including sheets and plates, foils and can sheets) account for 33.3% of all the circulating aluminum [3]; in consequence, fostering resources efficiency strategies in the field of sheet components could lead to a significant environmental impact reduction. Recycling aluminum by remelting is the most used strategy, it is still an energy-intensive one though. The overall energy efficiency is very low [3] and, more importantly, permanent material losses can occurs during remelting because of oxidation [4]. Besides conventional recycling, other strategies can be adopted to put in place more efficient material recovery strategies [5]. Cooper and Allwood [6] identify Reshaping strategy as one of the four (Remanufacturing, Reshaping, Relocation, Cascade) main approaches to reuse metals.

Sheet forming processes could play a significant role in fostering the reshaping strategy, as it means applying shaping processes to obtain a new geometry. Very few scientific publications can be found in literature dealing with sheet metal component reshaping. The main idea of the already proposed approaches concerns the possibility to take advantage of both flexibility and improved material formability provided by innovative sheet forming technologies [7]. Brosius et al. [8] proposed an automotive engine-hood reshaping by turning it into a sheet metal rectangular component by using sheet hydroforming processes. Takano et al. [9] applied incremental forming processes to reform sheet characterized by non uniform thickness The reshaping process include the flattening of a previously bent sheet and a subsequent incremental forming step. Abu-Farha and Khraisheh [10] used super plastic sheet forming for applying reshaping strategies to magnesium based components. A first paper dealing with the challenge of residual formability for sheet-metal products reshaping has been recently published [11].

The mentioned approaches are still preliminary and there is a research need in this domain, actually the potential of metal shaping processes as used as reshape option is not explored. Technological, economic as well as environmental feasibility of such a reuse approach should be deepened. Strengths and weaknesses of sheet components reshaping should be outlined. The present paper aims at starting to cover this research gap, specifically an early modeling effort to quantify the potential environmental impact reduction by means of reshaping is proposed. Primary energy demand for conventional recycling and reshaping are quantified and compared. Primary energy savings obtainable for an aluminum hood reshaping for different production scenario are quantified.

Nomenclature

m_i(kg)	mass of the component to be recycled/reshaped;
E_{CS}(MJ)	primary energy demand, conventional recycling route (from end-of-life component to starting blank);
E_{RS}(MJ)	primary energy demand, reshaping route (from end-of-life component to starting blank);
E_v(MJ/Kg)	embodied energy for the production of the material (energy that must be commuted to create the usable material from ores and feedstock);
E_R	embodied energy, secondary production (energy that must be committed to create the usable material from recycling scraps)
r	recyclability (fraction of material recycled at the end-of-life);
E_{hom}(MJ/Kg)	primary energy, homogenization step;
E_{hr}(MJ/Kg)	primary energy, hot rolling process;
E_{cr} (MJ/Kg)	primary energy, cold rolling process;
E_{an} (MJ/Kg)	primary energy, annealing step;
E_S(MJ/Kg)	extra energy to turn cast ingot into sheet;
E_{SM} (MJ/Kg)	part of the Es due to extra material used;
E_{SE}(MJ/Kg)	part of the Es due to extra post remelting/melting processes;
E_{Resh}(MJ/Kg)	embodied energy Reshaping process;
η	total material yield (post remelting processes plus laser cutting scraps) $\eta=\eta_{hr}\eta_{cr}$;
η_{hr}	material yield of hot rolling process;
η_{cr}	material yield of cold rolling process;
w	fraction of material suitable for reshaping $0 \leq w \leq 1$;
ΔE(MJ/Kg)	difference in forming process energy demand between conventional and reshaping route;

2. How to account for recycling credits

In order to account for the effective impact related to material production, credits deriving from aluminum recycling have been considered. It is worth pointing out that there is no single universally acceptable criterion to account for recycling benefits. Nevertheless, some useful guidelines are provided by Hammond and Jones [12]; mainly two principal methods, to deal with environmental credits arising from recycling, can be used: the recycling content approach and the substitution method. In the present paper the substitution method has been used, this method allocates the environmental credit of recycling to the end-of-life stage. The effective energy ascribable per Kg of material can be calculated applying equations 1.

$$E_{Substitution\ method} = E_V - r \cdot (E_V - E_R) \qquad (1)$$

From equation 1 it is possible to notice that the benefit arising from recycling is accounted for by taking away, from the primary production embodied energy Ev, the saved energy consumption $r \cdot (E_V - E_R)$. Such energy saving is obtained by recycling the material at the end of the component life. It is worth pointing out that the CO_2 emissions can be computed accordingly.

3. The proposed model

In order to model the energy saving obtainable by reshaping approach, a closed loop material flow was implemented. Actually, the reshaping based route was compared with the conventional recycling approach. The primary energy demand of both the approaches has been, therefore, modeled. As the reshaping approach uses an end-of-life aluminum sheet component as input material, the conventional recycling route has been modeled considering a closed loop material flow. In other words, for both primary and secondary aluminum production all the materials and energy flows to get aluminum sheet was modelled. This choice was driven by the will to make the comparative analysis reliable and to identify actual advantages of reshaping practices. Specifically, assuming m_i the mass of the end-of-life sheet component to be recycled/reshaped, the primary energy demand to recycle the mass m_i in the shape of sheet was modeled. In consequence, the selected functional unit to develop the comparison on is the closed loop recycling/reshaping of one sheet based component whose weight is as high as m_i. It is worth pointing out that for most of engineering materials databases reporting primary as well as secondary embodied energies exist [13,14]. These data consider the material production until cast ingot obtainment, therefore all the extra process steps to get the sheet have been modelled in the present research. Since there are no available models for reshaping, in this paper the formula of substitution method (equation 1) has been adapted for this specific application. The following subsections describe the modeling effort for conventional (section 3.1) and reshaping (section 3.2) approaches.

3.1. The conventional recycling route

Figure 1 depicts the energy and material flows for conventional recycling route. It is worth pointing out that values available in the databases consider the processes until remelting stage. Post-remelting processes such us thermal treatments and rolling processes are necessary to obtain aluminum sheets; such process steps characterize both primary and recycling routes. This is the reason why the energy demand Es was added to both Ev and E_R values in the substitution formula. The final formula results as reported in equation 2. It is worth pointing out that Es is made of two components: the contribution due to the extra material to be added to compensate yield losses (E_{SM}) and the post-remelting processing energy (E_{SE}). Such contributions can be calculated by using equations 4 and 5. For a given case study characterized by a mass m_i the total primary energy demand can be quantified by multiplying equation 2 by the mass m_i of the component to be recycled.
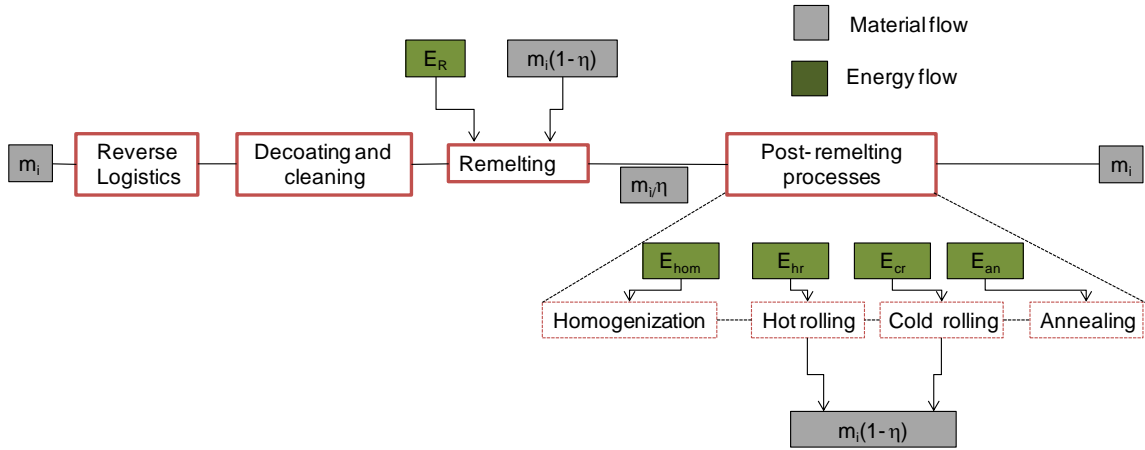
Fig. 1. Conventional sheet recycling route

$$E_{CS} = E_V + E_S - r \cdot (E_V - E_R) \tag{2}$$

$$E_S = E_{SM} + E_{SE} \tag{3}$$

$$E_{SM} = (1 - \eta)(E_V - r \cdot (E_V - E_R)) \tag{4}$$

$$E_{SE} = \frac{1}{\eta} \left(E_{hom} + E_{hr} + \eta_{hr} E_{cr} + \eta_{hr} \eta_{cr} E_{an} \right) \tag{5}$$

3.2. The reshaping route

Figure 2 depicts the energy and material flow for sheet component reshaping. It is worth pointing out that for a given component weighting m_i, part of the material ($m_i(1-w)$) can be cut off either during disassembly or during laser cutting to prepare the actual blank for final forming processes. The cut off material has been awarded an E_{CS} unit energy value to be consistent with the closed loop approach. Concerning the part of the component undergoing to reshaping route, decoating as well as the inspection step have to be considered. The latter stage concerns the end-of-life component inspection to verify the feasibility of the reshaping processes. This step can be based on visual inspection or can envisage a digitalization step (optical or laser based) to carry out the thinning distribution of the component and better design the subsequent forming step. Moreover, a further contribution equal to ΔE has been included; this value enables the difference in energy demand during forming processes to be considered. In fact, reshaping might require flexible sheet metal forming processes (hydroforming, Incremental forming, etc.,) instead of conventional stamping. Such process category, depending on the batch size, could require extra energy[15]. Moreover extra forming processes such us flattening [9,11] or heat treatments (annealing for work hardening removal) could be envisaged. All these contributions should be considered in the comparative analysis and can be accounted for by the component ΔE.

$$E_{RS} = (1 - w)E_{CS} + w[(E_V + E_S) - r(E_V + E_S - E_{Resh})] \tag{6}$$

Assuming r=1;

$$E_{RS} = (1 - w)E_{CS} + wE_{Resh} \tag{7}$$
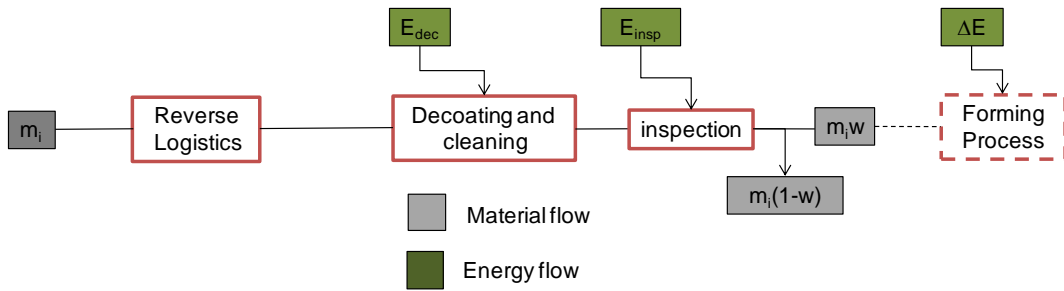
$$E_{Resh} = E_{dec} + E_{ins} + \Delta E \tag{8}$$

Fig. 2. Sheet reshaping route

4. The obtained results

The models have been applied to a specific case study: a 12.7 kg series 6000 aluminum hood of a mid-size car has been considered. Specifically, it is assumed that the hood is reshaped into another component by applying stamping processes (either conventional stamping or hydroforming processes). Hood is a suitable case study for such an approach as it is a large panel characterized by low strain values at its first forming step. In consequence, it can undergo further deformation as it is characterized by a proper residual formability. The used data for implementing the model along with the main references are reported in table 1. Different configurations have been analyzed; specifically different w values have been considered (from 1 to 0) as well as two different ΔE values. Concerning ΔE, two different scenarios have been considered: a base one characterized by ΔE=0, and a scenario with ΔE=8.77 MJ/kg where all the possible extra energies have been included. In the latter scenario the energy for flattening, heating and the difference in forming process between conventional stamping and hydroforming has been considered. The results for the two different scenarios with varying w values are reported in figure 3. Primary Energy for each recycling route as well as percentage values concerning Primary Energy savings are reported. Overall it is possible to notice that the reshaping approach is always the best option for all the analyzed scenarios. It is worth pointing out that when w=1 the whole end-of-life component is used for reshaping, while if w=1 no part of the component is considered suitable for reshaping. Energy savings are significant especially for higher value of w for both of the analyzed scenarios. Of course the difference between the two approaches decreases as the w value increases but the conventional recycling approach never outperforms the reshaping based one. Even though considering a ΔE=8.77 worsen the performances of the reshaping approach, it is the most energy efficient solution for all the considered w values.
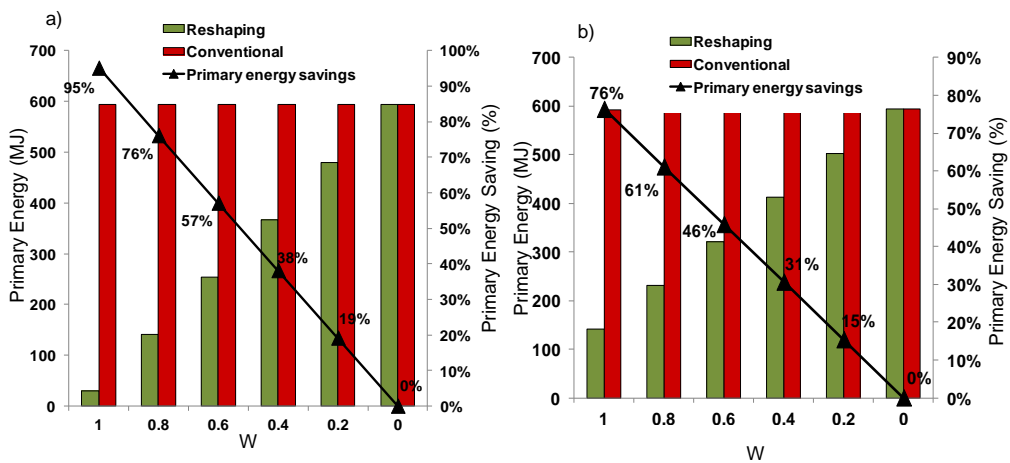

Fig. 3. Primary energy comparative results for ΔE=0 (a)and for ΔE=8.77(b)

Table 1. Used values for implementing the models

	Value	Reference
m_i	12.7	
E_V(MJ/kg)	210	[13][14]
E_R(MJ/kg)	26	[12]
r=recyclability	0.95	[4]
E_{hom}(MJ/kg)	1.40	[16]
E_{hr}(MJ/kg)	1.85	[16]
E_{cr} (MJ/kg)	1.30	[16]
E_{an} (MJ/kg)	1.20	[16]
η	0.85	
η_{hr}	0.90	[16]
η_{cr}	0.95	[16]
W	1-0	
ΔE (MJ/kg)	0 and 8.77	[15][16]
E_{dec}	2.30	[17]

5. Conclusions and further developments

In the present research a model for evaluating potential energy saving obtainable by means of reshaping is presented. An aluminum based component is considered as case study and both conventional and reshaping route primary energy demands have been modeled and compared. Results revealed that reshaping is always the more efficient solution across the analyzed scenarios. This study, therefore, reveals that such a material reuse approach could lead to significant environmental impact reduction. On the other hand reshaping of sheet metal based component is at its embryonic state and further research should be developed to address the following open issues:

- identifying the sheet based end-of-life components suitable for reshaping;
- identifying proper inspection and decocting procedure;
- defining guidelines for reshaping process design (identifying: intermediate forming steps, heat treatments, sheet forming process)
- analyzing reverse logistics issues;
- analyzing the actual profitability and the related business model.

References

[1] E. Worrell, J. Allwood, T. Gutowski, The Role of Material Efficiency in Environmental Stewardship. Annu. Rev. Env. Resour. 41 (2016) 575-598.
[2] J.M. Allwood, M.F. Ashby, T.G. Gutowski, E. Worrell, Material efficiency: A white paper. Resour. Conserv. Recy. 55 (2011) 362-381.
[3] G. Liu, E.C. Bangs, D.B. Müller,. Stock dynamics and emission pathways of the global aluminum cycle. Nat. Clim. Change 3 (2013) 338-342.
[4] J.R. Duflou, E. Tekkaya, M. Haase, T. Welo, K. Vanmeensel, K. Kellens, W. Dewulf, D. Paraskevas, Environmental assessment of solid state recycling routes for aluminium alloys: can solid state processes significantly reduce the environmental impact of aluminium recycling? CIRP Ann. Manuf. Technol. 64 (2015) 37-40.
[5] G. Ingarao, Manufacturing strategies for efficiency in energy and resources use: the role of metal shaping processes. J. Clean. Prod., in press (2016) DOI: 10.1016/j.jclepro.2016.10.182 .
[6] D.R. Cooper, J.M. Allwood, Reusing steel and aluminum components at end of product life. Environ. Sci. Technol. 46 (2012) 10334-10340.
[7] G. Ingarao, R. Di Lorenzo, F. Micari, Sustainability issues in sheet metal forming processes: an overview. J. Clean. Prod. 19 (2011) 337-347.
[8] M. Brosius, N. Hermes Ben Khalifa, M.Trompeter, A.E. Tekkaya, Innovation by forming technology: motivation for research. Int. J. Mater. Form. 2 (2009) 29-38.
[9] H.Takano, K. Kitazawa, T. Goto, Incremental forming of non uniform sheet metal: Possibility of cold recycling process of sheet metal waste. Int. J. Mach. Tool. Manuf. 48 (2008) 477-482.

[10] F.K. Abu-Farha, M.K. Khraisheh, An integrated approach to the Superplastic Forming of lightweight alloys: towards sustainable manufacturing. Int. J. Sustain. Manuf. 1 (2008)18-40.

[11] J. Falsafi, E. Demirci, V. V. Silberschmidt, Computational Assessment of Residual Formability in Sheet MetalForming Processes for Sustainable Recycling. Int. J. of Mech. Sci. 119 (2016) 187–196.

[12] G. Hammond, C. Jones, Inventory of Carbon and Energy (ICE), Annex B: How to Account Forrecycling a Methodology for Recycling. The University of Bath, Bath, UK, 2010.

[13] M.F. Ashby,. Materials and the Environment. Butterworth Heinemann/Elsevier, 2013.

[14] T.A. Mayyas, A. Qattawi, A.R. Mayyas, M.A.Omar, Life cycle assessment based selection for a sustainable lightweight body-in-white design. Energy 39 (2012) 412-425.

[15] M.A. Dittrich, T.G. Gutowski, J. Cao, J.T. Roth, Z.C. Xia, V. Kiridena, F. Ren, H. Henning, Energy analysis of incremental sheet forming. Prod. Eng. Res. Dev. 6 (2012) 169-177.

[16] R. L. Milford, Allwood J.M., J. M. Cullen, Assessing the potential of yield improvements, through process scrap reduction,for energy and CO2 abatement in the steel and aluminium sectors. Res. Cons. and Rec. 55 (2011) 1185– 1195.

[17] M. D Swanson, R.A. Miller, J.J. Aardsma, M. J. Chimack. E2 and P2 Improvement Opportunities in Secondary Aluminum Processing: A Case Study. ACEEE Summer Study on Energy Efficiency in Industry 1 (2005)171-191