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ScienceDirect

Procedia CIRP 48 (2016) 194 – 199

www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

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.

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering

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].

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.044

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.

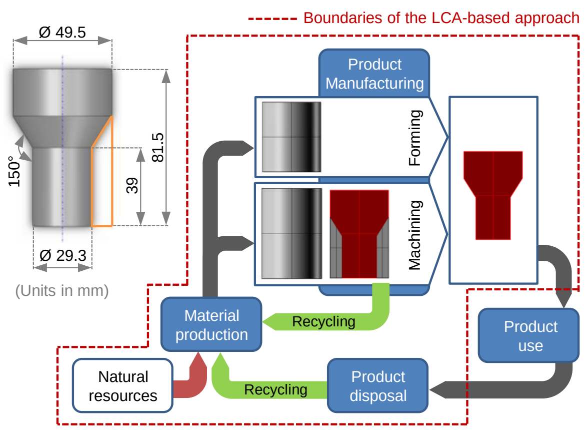

Fig. 1. LCA-based approach for process comparison.

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.