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Subtractive versus mass conserving metal shaping technologies: an environmental impact comparison

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ABSTRACT

The scientific studies in the domain of environmental sustainability of metal processing technologies predominantly focus on conventional material removal processes, as milling and turning. Despite some exceptions, many other non-machining technologies, such as metal forming processes, are still not well documented in terms of their energy and resource efficiency. Moreover, to properly evaluate the environmental impact of a given process, a standing-alone approach is no longer sufficient. In order to offer a valuable contribution in the domain of metal shaping sustainability, the present paper proposes a thorough methodology entailing to compare, from the environmental point of view, two traditional technologies: a hot extrusion process (mass conserving approach) and a turning (subtractive) one. A Life Cycle Assessment (LCA) based approach is implemented to properly analyze the considered processes. An axi-symmetric aluminum component was selected to develop the analysis on. Besides the analysis of material flows occurring all along the life cycle of the component, the material use and the consumed electrical energy necessary for the tools manufacturing are measured to properly quantify the environmental impact of the production phases. The most relevant influencing factors within each technology are identified and quantified. Moreover, an analysis of the environmental performance of the two processes at the varying of the batch size is presented. The paper aims at providing some general guidelines for the identification of the greenest technology as the main influencing factors change.

1. Introduction

It is by now well known that reducing CO_2 emissions is an urgent objective to pursue. Such statement is true at a global scale, and it is particularly true as the industrial sector is concerned. Many initiatives in the domain of energy and resource efficiency have already been launched at a worldwide scale. Nevertheless, world CO_2 emission rose by 2.7% over 2011. The industry plays a relevant role, and it accounts almost for the 40% of the total consumption (IEA, 2013). The indirect emissions, caused by the use of electricity, currently represent the 18% of the total amount. This scenario becomes dramatic if the appraisals from the International Energy Agency are considered: by 2035 the demand for electricity will increase by 70%. The scientific as well as the industrial world have gathered such challenge, starting to find out energy and resource efficient manufacturing strategies (Duflou et al., 2012).

When a component has to be produced, in most cases more than one manufacturing technology can be used. In the recent past, the technology to be implemented was selected mainly on the basis of cost, productivity, or technical indicators. Nowadays, such criteria are no longer sufficient, and the environmental impact has to be considered in the decision step. As long as the technological feasibility of a given process is guaranteed, processes minimizing resources and energy consumption have to be selected to manufacture a given part. The here proposed research aims at analyzing different production technologies, i.e. two different ways to shape metal components: a mass conserving (forming process) and a subtractive approach (machining process). Material plays a relevant role as the environmental impact of a product is concerned. Minimizing material use in production is, therefore, an important strategy to pursue for reducing the CO_2 footprint of a given component. Material scraps should be minimized even when benefits deriving from recycling are considered. The comparison of two technologies characterized by different amount and kind of materials could lead to interesting conclusions in the domain of CO_2

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emission minimization. As a more general issue, the manufacturing world has to face concerns the finding of new technologies, and such futures technologies cannot leave sustainability concerns out. A systematic analysis and comparison of processes is an urgent research to develop. As a matter of fact, such kind of research can help in identifying the manufacturing strategy able to satisfy the new market and society requirements: high complexity, lightweight and "green" products.

1.1. Literature review

In order to select the proper technology, a full awareness about the environmental impact of all the existing technologies should be available. In this respect, the CO_2PE! initiative has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact of a wide range of available and emerging manufacturing processes, and to provide guidelines to improve them. The growing interest in quantifying the CO_2 footprint of manufacturing processes led to the development of a methodology for the systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) (Kellens et al., 2012). Nevertheless, nowadays the reported studies on sustainability analysis of metal processing predominantly focus on conventional material removing processes, such as turning, milling, and grinding.

Some researchers focus on the measurement, quantification, and minimization of electric energy consumption. Devoldere et al. (2007) discussed about the potential for energy improvement, with particular attention to the fixed energy demand of machine tools, the importance of their architecture, and the production modes share. The research developed by Diaz et al. (2010) dealt with the effect of the material removal rate on electric energy consumption, whilst Kara and Li (2011) presented an empirical model to characterize the relationship between energy consumption and process variables for material removal processes. Avram and Xirouchakis (2011) offered an energy consumption reduction perspective by considering alternative machining strategies, with respect to various use-phase regimes of a machine tool system. Campatelli et al. (2014) proposed a response surface based approach to model the power consumption in a milling process performed on a modern CNC machine. Balogun and Mativenga (2013) defined a mathematical model for predicting the direct electrical energy requirements in machining processes, taking into account the machine tools' architecture, the operational productive mode, and the sub-unit power consumption. A further energy consumption model for the milling process was presented by Li et al. (2013): an improved model, as a function of material removal rate and spindle speed, was tested and validated under various cutting parameters. An optimization approach was also proposed by Bhushan (2013). In particular, the machining parameters were optimized by multi-response considerations, namely power consumption and tool life, during machining of 7075 Al alloy with 15 wt.% SiC particle composites. Yan and Li (2013) developed a multi-objective optimization method for cutting parameters in milling, to evaluate the trade-offs between sustainability, production rate and cutting quality.

Others researches in the domain of machining process sustainability focus on the effect of cutting fluids. A critical review on the lubrication techniques in machining was presented by Lawal et al. (2013), while Lawal et al. (2014) compared the cutting performance of vegetable cutting fluids and mineral oil-in-water emulsion when turning an AISI 4340 steel. Davoodi and Tazehkandi (2014) analyzed the effect of cutting speed and undeformed chip thickness on cutting and feed force components, and the tool tip temperatures were experimentally investigated to remove the cutting fluid. Sharma and Sidhu (2014) investigated the effect of dry and near-dry machining on an AISI D2 steel, by using a vegetable oil.

Other researchers focus on a global approach aimed at studying all the environmental influencing factors of machining processes. Gutowski et al. (2006) and Gutowski (2009) presented an environmental analysis carried out at a system level. In particular, a qualitative investigation was made, concerning the impact of the material removal process itself as well as the impacts related to material production, cutting fluid preparation, tool and machine tool construction. Gutowski et al. (2006) proposed a model able to calculate the electricity requirements for a manufacturing process, as a function of the process type and of the rate of the material processing. It is worth pointing out that, in this approach, process parameters such as processing rate, workpiece hardness and specific cutting mechanics can be considered in the model. Narita et al. (2006) proposed a theoretical model able to evaluate the environmental burden of a machining operation, by taking into account several factors: electric energy consumption, cutting tool status, coolant quantity, lubricant oil quantity and metal chip quantity. An interesting research was also developed by Rajemi et al. (2010): the aim of their work was to create a new model and a new methodology for optimizing the energy footprint of a machined product. In this research the environmental impact of cutting tool was included in the sustainability analysis. A recent example of global machining processes modeling can be found in the work of Kuram et al. (2013): the effects of cutting fluid types were investigated as a function of three milling factors (cutting speed, depth of cut, and feed rate) on process responses (specific energy, tool life, and surface roughness). Mono- and multi-objective optimization studies were conducted using the responses as objectives to optimize. A further innovative approach was developed by Díaz-Tena et al. (2014), in which the use of bacteria in machining was considered as a renewable natural source of tools. As far as grinding is concerned, an overview on the sustainability of the processes (analyzing the environmental, social, and economic point of view) was recently published by Aurich et al. (2013). Winter et al. (2014) presented a Pareto-based approach for characterizing the grinding processes in terms of their technological, economic and environmental impact; a new methodology to determine optimal process parameters to improve eco-efficiency was presented as well.

In literature some exception on environmental analysis of non-machining technologies can be found. In particular, Kellens (2013) analyzed, by using a systematic approach, the environmental performance of laser cutting, Selective Laser Sintering (SLS) and Electric Discharge Machining (EDM). Recently, some research groups published environmental analyses on additive manufacturing. Kellens et al. (2014a,b) provided accurate estimations of the environmental footprint of SLS processes based on two design features. Their research concerned energy and resource consumption as well as process emissions. Le Bourhis et al. (2013) presented a new methodology in which all the resource flows (material, fluids, electricity) were considered in the environmental impact assessment. Baumers et al. (2012) discussed the implementation of a tool for the estimation of process energy flows and costs occurring in the direct metal laser sintering.

In contrast to the conventional machining processes (e.g. milling, turning, etc.), metal forming processes are still less documented in terms of their energy demand (Ingarao et al., 2011). In particular, only a few studies related to the environmental impact of sheet metal forming processes can be found in literature. The most relevant contributions concern air bending (Santos et al., 2011) and incremental forming (Ingarao et al., 2014; Dittrich et al., 2012). Recently, a paper reporting a structured overview of the available studies on the energy demand of sheet metal forming