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A comprehensive analysis of electric energy consumption of single point incremental forming processes

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ABSTRACT

Production processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, but are still poorly documented in terms of environmental impact. The present paper proposes a comprehensive energetic analysis of Single Point Incremental Forming Processes (SPIF). The three most commonly used machine tool architectures able to perform SPIF operations have been taken into account: a CNC milling machine, a six-axes robot as well as the dedicated AMINO machine tool were analyzed from an electrical energy consumption point of view. For all the setups, a working cycle time study and power study were performed. Moreover the contribution of each sub-unit towards the total energy demand has been determined. The influence of the most relevant process parameters (e.g. feed rate, step down), has been determined. The three setups have been analyzed in order to identify the solutions with the highest energy efficiency for SPIF processes and a set of potential environmental friendly process control strategies are proposed. Finally, a parametric model, able to predict the energy consumption at the varying of the process parameters, is proposed.

1. Introduction

Manufacturing processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products. Nevertheless such processes, in particular non-conventional production processes, are still poorly documented in terms of environmental footprint. Thus, a thorough analysis on the causes affecting the environmental impact of these processes is necessary. In this respect, the CO_2PE!-Initiative (CO_2PE!, 2013) has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes and to provide guidelines to improve these. In particular the objective of the CO_2PE! initiative is to cluster forces in different continents, involving machine builders as well as academics, to analyze existing and emerging manufacturing processes for their ecological impact in terms of direct and indirect emissions.

A methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) is provided by Kellens et al. (2012). Duflou et al. (2012) provide a comprehensive overview of the state of the art in energy and resource efficiency improvement methods and techniques in the domain of discrete part manufacturing, with attention to the effectiveness of the available measures.

1.1. Literature review

From the literature review in the domain of environmental impact of production process it is possible to notice that nowadays the reported studies in the domain of metal forming processing predominantly focus on conventional material removing processes such as turning, milling and grinding; dealing with the influence of material removal and cutting fluids, in parallel with the electricity consumption. Gutowski (Gutowski et al., 2006; Gutowski, 2009) presented an environmental analysis of machining processes carried out at 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 proposes 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

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hardness and specific cutting mechanics can be considered in the model. Shao et al. (2004) present a power model where process parameters (cutting speed, feed rate, depth of cut, work-piece material and tool material) as well as tool flank wear are taken into account for face milling operations. Another early research on machining processes energy analysis can be found in Devoldere et al. (2007). This study paper discusses potential for energy improvement measures with particular attention to the fixed energy demand of machine tools, the importance of machine tools architecture and production modes share is discussed.

An important recent contribution on energy consumption characterization for machining processes was developed by Diaz et al. (2010). In this paper, some process parameters were varied in order to evaluate the influence on energy consumption during a machining operation.

Kara and Li (2011) present an empirical model to characterize the relationship between energy consumption and process variables for material removal processes. The methodology has been tested and validated on a number of turning and milling machine tools.

Avram and Xirouchakis (2011) propose a research on the energy requirement at machine tool level in machining processes. This paper offers an energy consumption reduction perspective by considering alternative machining strategies and system components interactions translated into variable and constant power flows with respect to various use phase regimes of a machine tool system.

An interesting research was developed also by Rajemi et al. (2010): the aim of their work was to develop a new model and new methodology for optimizing the energy footprint for a machined product. The total energy of machining a component by the turning process was modelled and optimized, the paper clearly identifies critical parameters in minimizing energy use.

More recently some researchers (Campatelli et al., 2013) focused on the efficiency of the machining centres and provided an experimental approach to evaluate and optimize the process parameters in order to minimize the power consumption in a milling process performed on a modern CNC machine. The machine tools production mode shares are analyzed and the process has been modelled by using a response surface method.

A further effort in modelling power consumption of machining processes can be found in Balogun and Mativenga (2013). The aim of this research was the development of a new mathematical model and logic for predicting direct electrical energy requirements in machining tool paths. The influence of three factors on the total energy demand during machining operations was analyzed: machine tools architecture, the operational productive mode and the sub-unit power consumption.

An optimization approach has been also proposed (Bhushan, 2013) to evaluate the contribution of cutting parameters during machining of 7075 Al alloy 15 wt% SiC composite on the power consumption and on tool life by using response surface methodology. Optimum values of cutting parameters to minimize the power consumption and maximize tool life have been found out by desirability analysis.

Another recent exemplum of modelling and optimization of machining processes can be found in Kuram et al. (2013). In this study the effects of cutting fluid types are 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). D-optimal method was implemented to develop mathematical models for process responses. Mono and multi objective optimization studies are conducted using specific energy, surface roughness and tool life as objective to optimize.

Yan and Li (2013) developed a multi-objective optimization method based on weighted grey relational analysis and response surface methodology, which is applied to optimize the cutting parameters in milling process in order to evaluate trade-offs between sustainability, production rate and cutting quality.

Li et al. (2013) present another energy consumption model to characterize the relationship between process parameters and energy consumption for material removal processes based on thermal equilibrium and empirical modelling. The improved model of milling process as a function of material removal rate and spindle speed has been tested and validated under various cutting parameters. Experimental results show that the improved model is able to provide a reliable prediction of energy consumption for given process parameters with an accuracy of more than 96%.

As far as the grinding processes are concerned, while an initial analysis on force and power consumption can be found in Brach et al. (1987), a very recent overview on the sustainability of the process has been recently published by Aurich et al. (2013), in this latter study the abrasive processes have been analyzed from the environmental, social and economic points of view.

Winter et al. (2013) present a Pareto based approach for characterizing grinding processes in terms of their technological, economic and environmental impact; a novel methodology to determine optimal process parameters to improve eco-efficiency for grinding processes is presented as well.

As it can be deduced from the reported literature analysis on conventional material removal processes sustainability evaluation, the researchers are focussing their effort on the possibility to well model and predict the environmental impact of chipping processes.

In literature some exception on non-machining technologies environmental analysis can be found (Chiarini, 2013); in particular some studies are reported on the additive manufacturing processes. Morrow et al. (2007) investigate three case studies to reveal the extent to which DMD-based manufacturing of moulds and dies can currently achieve reduced environmental emissions and energy consumption relative to conventional manufacturing pathways. This research effort has produced a quantitative estimation of the energy consumption and emissions associated with the production of mould and die tooling via laser-based Direct Metal Deposition (DMD) and CNC milling. Baumers et al. (2012) present the implementation of a tool for the estimation of process energy and costs in the additive manufacturing technology variant direct metal laser sintering. Kellens et al. (2013) provide accurate estimations of the environmental footprint of Selective Laser Sintering (SLS) processes based on two design features the research concerns energy and resource consumption as well as process emissions for SLS processes.

Serres et al. (2011) compare an innovative additive laser technology (CLAD) with a conventional machining process by applying an LCA approach: both material and energy consumptions are quantified and compared.

Other researchers compare innovative laser assisted processes with conventional one from an environmental point of view: Zhao et al. (2010) evaluate and compare the environmental performance of laser assisted processes with traditional methods. In this research two representative laser based processes, i.e. laser shock peening of 7075-T7351 aluminium and laser assisted turning of compacted graphite iron have been analyzed.

Despite some exceptions many other non-machining technologies, such as sheet metal forming processes, are still not well documented in terms of environmental impact. The evaluation of the environmental performance of metal forming processes (Bulk and sheet) is an urgent topic to be investigated since there is still a lack of knowledge in terms of analysis and modelling of their environmental impact. For cold sheet metal forming processes the main concerns are related to the electrical energy usage as well as material waste reduction (Ingarao et al., 2011)