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Optimization of process parameters using a Response Surface Method for minimizing power consumption in the milling of carbon steel

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ABSTRACT

Due to the urgent need for global reductions of environmental impacts, many studies have been carried out in different fields. One of the most important sectors is manufacturing, particularly due to the high power consumption of the production machines of manufacturing plants. This paper focuses on the efficiency of the machining centres and provides 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 parameters evaluated are the cutting speed, the axial and radial depth of cut, and the feed rate. A lubrication strategy has been chosen based on previous studies: all the tests have been carried out using dry lubrication in order to eliminate the environmental impact due to lubricant without substantially affecting the energy consumption. The process has been analyzed using a Response Surface Method in order to obtain a model fit for the fine tuning of the process parameters.

1. Introduction

One of the most relevant challenges in modern manufacturing is the need to reduce the environmental impacts of production as far as possible. Often the production companies seek to change drastically their technologies in order to adopt a greener approach. Unfortunately this is not a choice for every product: sometimes alternative and greener technologies for manufacturing a specific component do not exist and thus it is necessary to implement an incremental improvement of the current technology. This is often the case for products manufactured by milling, which usually have strong constraints due to the required surface finish and geometrical complexity which cannot be obtained using alternative technologies.

The EU Commission recognized that machine tools play a very important role in this scenario. Their efficiency is so crucial that this type of product has been proposed for inclusion in the product categories regulated by the Ecodesign Directive (EPTA, 2007). Also, the Kyoto Protocol (United Nations Framework Convention on Climate Change, 1997) reports on the importance of achieving reductions in energy use through the development of different design features of machine tools by machine tool designers. Another crucial issue is related to machine tool users: an increase in efficiency could also be obtained by developing more efficient machine tool motions and tool paths.

Moreover, interest in using green manufacturing strategies is steadily increasing in manufacturing companies, mainly due to two reasons: the environmental cost of production is taken into account by an ever-increasing number of governments and depletion of world resources is occurring so material and energy costs are increasing (i.e. the trend in the cost of iron is very well known by mechanical companies). With these boundary conditions it is necessary to focus the research efforts in order to create greener manufacturing strategies.

The objectives of green manufacturing are summarized well by the 12 principles of Anastas and Zimmermann (Anastas and Zimmerman, 2004); in particular the science of manufacturing has the task of reducing the environmental impact of its processes through parameter optimization and/or changes of technologies and materials.

In the product design field, many studies have been carried out in order to evaluate the environmental impact of certain materials or technical solutions, thanks to the development of structured and database-based tools such LCA (Life Cycle Assessment, defined by the ISO 14000 standards) followed by LCM (Life Cycle Management). These analyses add new value to the product, helping the diffusion of ISO 14001 certification among production companies; the feasibility and advantages are already well documented (Orecchini, 2000; Caspersen and Sorensen, 1998). However in these analyses the technology plays a very unimportant role: most of the databases offer only a crude evaluation of the environmental

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impacts of a specific technology (i.e. the Ga.Bi. database), driving the designer to choose a new technology instead of providing a tool for the optimization of the current one. In Europe (2009 data from Europe's Energy Portal, 2012), about 24% of the primary energy consumption is used by the industry and a margin for improvement of about 30% has been estimated. Fig. 1 shows the Italian 2010 power consumption data by sector, while Fig. 2 presents a detailed analysis of the industrial sector; the data reported in these figures have been available on the website of the Italian energy distributor, TERNA (2010 data from TERNA website, 2012). From these data the significant contribution due to machining is evident.

Many actions could be carried out in order to reach this goal: the development of zero defect processes, the implementation of net shape processes, the use of reusable materials, and the reduction of resource consumption by production machines. While the first actions require very consistent investment in order to drastically change production technologies, the last approach could be applied easily in order to maintain the same production system while simply optimizing its process parameters. Moreover, optimizing existing processes instead of making drastic changes has an intrinsically better economic and social sustainability due to the lower investment needed and user acceptance (Pusavec et al., 2010a, 2010b).

2. Analysis of the environmental impact of machining

The demand for environmentally friendly processes imposes a new perspective on the analyses carried out till now: one example is the study of the optimal lubrication strategy considering not only the surface finish or process stability but also new indicators such as the power consumption and the global environmental impact of such a manufacturing setup. Many authors have developed models to assess the environmental impact of machining operations and to fine tune this value. In order to obtain this result the first step is to develop a model that allows analytical analysis of the effect of process parameters on the environmental performance of the process itself.

In particular many studies have focused on the effect of cutting fluids on the environment (Lawal et al., 2013; Pusavec et al., 2010a, 2010b; Zackrisson, 2005) and alternative hybrid processes (Neugebauer et al., 2012). Coolant and lubricants are usually employed in machining operations, including turning, milling, drilling, or grinding, and they are able, in general, to improve machining performances, but there are also some risks associated with their use (Weinert et al., 2004; Soković and Mijanović, 2001; Cetin et al., 2011): these fluids are responsible for skin and breathing problems among machine operators. Furthermore, after their disposal, if recycling is not possible, they may become polluting agents in soil and water when inappropriately handled (Shashidhara and Jayaram, 2010). However a general result could be obtained from all these studies: flooded lubrication is an approach that induces a large environmental impact, and thus the route taken to reduce the environmental impact must lead to dry or nearly dry approaches, like MQL (Minimal Quantity Lubrication). In a previous work by the author (Campatelli, 2009) the effect of lubrication in a turning process was studied and its environmental impact was analytically evaluated in terms of both equivalent GWP (Global Warming Potential) and power consumption due to the accessory equipment (i.e. cutting fluid pump). The general result was that the most environmental friendly solution for cutting is dry lubrication, although MQL is also able to obtain good performance (+8% of the environmental burden with respect to dry lubrication). Moreover the use of dry cutting is encouraged by the reduction of the processing cost; it has been estimated that the cost of cutting fluids is approximately 7–17% of the total cost of the machining process (Klocke and Eisenblaetter, 1997). For newer milling tools for traditional materials, this saving is able to compensate for the greater cost of tooling due to the increase in tool wear, which is reduced by current high performance coatings. Thanks to these characteristics, dry machining is an emerging trend for traditional materials such as aluminium (Fratila and Caizar, 2011, Dhar et al., 2007) or low alloyed steel (Campatelli, 2009) but it can hardly be used for difficult-to-cut materials, for which MQL is becoming the best option (Devillez et al., 2007). Another advantage of dry machining is that the implementation of such an approach does not require structural changes in machine tools but only some adjustments regarding the tooling and cutting conditions.

Given the previous issues the choice for the experimental tests carried out was the use of dry machining.

Also, many studies have already been developed regarding the modelling of the machining processes, sometimes using analytical approaches and sometimes experimentally based ones. An important contribution has been the proposal of a standard definition of the machine tool state in order to have a taxonomy of the power consumption; in this field the CO2PE! Project (Cooperative Effort in Process Emission) proposed a unified taxonomy (Ostaeyen, 2010) and methodology (Kellens et al., 2012) so that energy data collection in manufacturing can be standardized and presented in a globally compatible approach. The two states are 'basic state' and 'cutting state'; this taxonomy allows some useful considerations to be highlighted in order to provide a functional model for machine tool power consumption. Some of these are reported in the work of Balogun and Mativenga (2013) and are briefly summarized here. The basic state power consumption comprises a higher percentage of total power consumption in modern machines compared to older machines, as shown by the work of Kordonowy (2001), Gutowski et al. (2006) and Dahmus and Gutowski (2004), where the fraction of power used by the

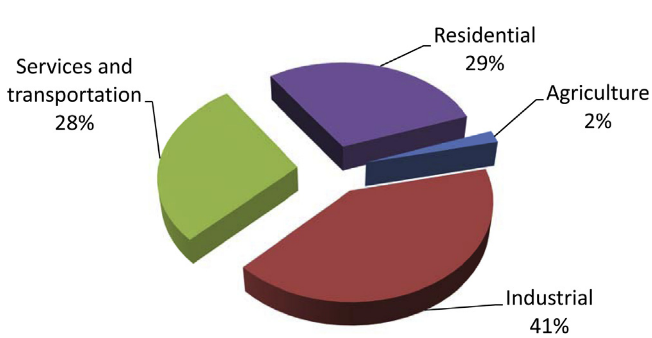

Fig. 1. Power consumption by sector in Italy (year 2010).

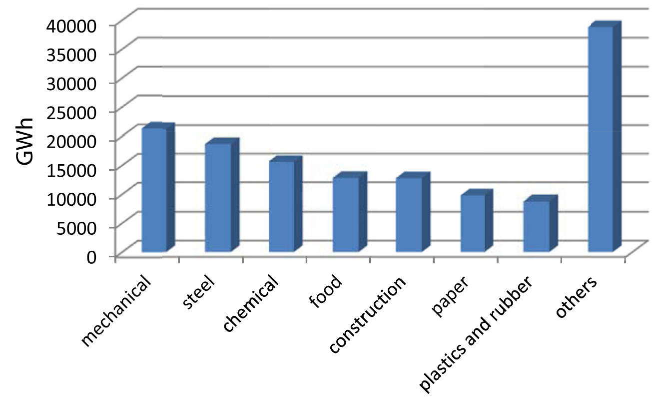

Fig. 2. Power consumption in Italy (year 2010) for the industrial sector in GWh.