Journal of Cleaner Production xxx (2015) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Multi-objective parameter optimization of CNC machining for low carbon manufacturing

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ARTICLE INFO

Article history:
Received 5 April 2014
Received in revised form
21 January 2015
Accepted 16 February 2015
Available online xxx

Keywords:
Processing parameters
Optimization
Carbon emissions
CNC machine

ABSTRACT

Low carbon manufacturing is of growing importance due to the severity of energy shortage and increasing energy costs, as well as a series of environmental problems, i.e., climate change and global warming. This paper investigates the potential of process parameter optimization to minimize carbon emissions during machine processing. A process model of CNC machining is first presented to scope the system boundaries for energy footprint and process efficiency. A multi-objective optimization model is then proposed to explore the impact of cutting speed and feed rate on carbon emissions and processing time. The benefit of the approach is illustrated through a case study of a CNC cylindrical turning process.

1. Introduction

CNC machining is a widely used processing method in mechanical manufacturing systems. Its cutting parameters are directly related to production quality, efficiency and cost. Our recent study found that carbon emissions of CNC-based machining systems vary with respect to cutting parameters (Li et al., 2013) as well. Thus understanding the relationship and developing techniques for parameter optimization is of extreme importance in improving overall system performance in terms of not only efficiency and costs, but also environmental impact.

A perusal of current literature provided a number of analytical formulations of cutting parameter optimization. A first group focused their work on single objective optimization. Saravanan et al. (2003) considered the optimization problem with respect to production cost for turning cylindrical stock into continuous finished profiles. Subramanian et al. (2013) analyzed the relationship between cutting parameters and cutting force, on which a parameter optimization model was proposed to minimize cutting force. Multi-objective optimization was also carried out by many researchers. Addona and Teti (2013) developed a genetic algorithm-based method to seek optimal cutting parameters in turning processes that lead to reduction in production cost and time as well as improvement in production quality. Thepsonthi and Özel (2012) focused on the micro-end milling process where a series of physical micro-milling experiments were first conducted on which the correlation of cutting parameters, surface roughness and burr formation were established based. Their optimization results via particle swarm method indicated that feed rate and cutting depth are the most influential parameters to surface roughness and burr formation.

The rising severity of energy shortage together with other environmental problems results in great efforts towards energy saving and emission reduction. Considering machine tools as the main sources of energy consumption in the industrial sector, a number of researchers were motivated to investigate the relationship of energy consumption with respect to machine activities and parameters. Gutowski et al. (2006) conducted a series of experiments to investigate the composition of energy consumption of machine tools as two parts: constant energy consumption and variable energy consumption. They found that the power consumption and energy consumption of processing machines were influenced by material removal rate. Schlosser et al. (2011) presented an approach for the evaluation of energy consumption of cutting processes. Their experimental observation indicated that an energetic trade off can only be achieved by changing process parameters comprehensively where positive or even negative synergy efforts might be anticipated. Behrendt and Zein. (2012) proposed

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http://dx.doi.org/10.1016/j.jclepro.2015.02.076
0959-6526/

Please cite this article in press as: Yi, Q., et al., Multi-objective parameter optimization of CNC machining for low carbon manufacturing, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.02.076

the use of standard assessment procedures to measure the power demands of machine tools. Kuram et al. (2013) investigated the effects of cutting fluid types as a function of three milling factors (i.e., cutting speed, cutting depth and feed rate) on process responses, such as specific energy, tool life and surface roughness. Jia et al. (2013) proposed a Therblig-based energy demand framework where machining processes are divided into a series of activities, and each activity is in one machining state with one or more Therbligs.

Apart from energy analysis of machine tools, another line of work sought for various strategies of energy reduction. Mori et al. (2011) conducted three case studies on power consumption reduction through high cutting condition, adaptive pecking during deep hole drilling, and synchronization of spindle speed and feed rate, respectively. Rajemi et al. (2010) considered the optimization of tool life for minimum energy of a turning process. The conflict and synergy between economical and environmental considerations as well as the effect of system boundaries in determining optimum machining conditions were also explored and discussed in their study. The work of Bhushan (2013) was similar to Rajemi et al. (2010) except that he focused on a particular machining process of Al Alloy SiC particle composites. More parameters, such as cutting speed, feed rate, cutting depth and nose radius, were considered in his approach that makes it more complex and practical. Hanafi et al. (2012) studied the optimization of cutting conditions for sustainable machining using gray relational theory and Taguchi method, aiming to achieve simultaneously the minimum power consumption and the best surface quality. Their results again confirmed that cutting speed and cutting depth are the most influential parameters. A similar work was carried out by Yan and Li (2013) with the emphasis on a weighting scheme for the impact of various milling parameters on sustainability, production rate and cutting quality. Their results indicated that width of cut is the most influential parameter, and low spindle speed is more energy efficient than cutting at initial speed for the milling process.

Understanding energy consumption of machine tools is necessary but not sufficient to quantify their environment impact. Therefore, the research on carbon emissions of manufacturing systems began to emerge. Tridech and Cheng (2008) explored theoretical models, characterization and implementation perspectives of low carbon manufacturing. Two operational models at supply chain and shop floor levels were then established and validated. Jeswiet and Kara (2008) introduced the concept of carbon emission signature on which the correlation of energy consumption and carbon emissions were established. Song and Lee (2010) proposed an estimation method for green house gas (GHG) of a manufacturing part. A seven-step low-carbon product design system was then developed, including the setup of GHG emission target, establishment of the bill-of-material (BOM) structure, and formation of the green gas BOM (g-BOM), etc.

To summarize the above literature review, the research of parameter optimization of machining tools has progressed from mono-objective on cost, quality or energy, to multi-objective. In the context of manufacturing, multiple characteristics of the system are necessary to be factored into optimal decision making. With the increasing concerns on material resources and energy conservation, more efforts have started to devote on the analysis of energy consumption and carbon emissions of machining tools. While few works, including our prior study (Li et al., 2013), investigated the correlation of carbon emissions and cutting parameters, how to achieve an optimum scheme with a balance of process efficiency and carbon emissions is yet undertaken. Motivated by these remarks, this paper makes contributions in two areas. First, a quantitative method is proposed to characterize various carbon emissions of CNC machining. With such a model, carbon emissions of machining with respect to cutting speed, feed rate, and cutting depth, can be mathematically represented and calculated. Second, a multi-objective optimization model that takes into consideration of production efficiency and carbon emissions is proposed and solved using a non-dominated sorting genetic algorithm (NSGA-II).

The rest of the paper is organized as follows. Section 2 models the relationship of process parameters and system responses. Section 3 presents the optimization problem and its mathematic representation. The solution through NSGA-II is then presented Section 4. The validity of this approach is demonstrated through a case study and the sensitivity analysis in Section 4. Our conclusion and future research is discussed in Section 5.

2. Process modeling of CNC machining

In order to optimize parameters for CNC machining, it is necessary to construct relationships between the responses and process parameters of interest. For low carbon manufacturing, this paper is primarily concerned on processing efficiency and carbon emissions of CNC machining. The most essential parameters that have influence on them are cutting speed v_c, feed rate f and cutting depth a_{sp} (Rajemi et al., 2010). In practice, the cutting depth is usually determined by machining allowance and accuracy requirement, which has relatively less influence on wearing of tools. So this paper only considers cutting speed and feed rate in the optimization process, but treats cutting depth as a constant.

2.1. Processing time function

The power profile of machining process of a CNC machine tool is shown in Fig. 1. In our case, we focus on the process time T_p begins from the time when the spindle rotating stately and feeding (processing start), to the time that processing is end and retracting cutting tool (processing end). It is modeled as the sum of cutting time, tool change time and auxiliary time, as shown in Eq. (1).

$$T_p = t_m + T_{tct} + T_{at} \tag{1}$$

t_m is the cutting time of the process, related to machining parameter and processing length:

$$t_m = 60 \times \frac{L_w \Delta}{n f a_{sp}} = 60 \times \frac{\pi d_0 L_w \Delta}{1000 v_c f a_{sp}} = \frac{3\pi d_0 L_w \Delta}{50 v_c f a_{sp}} \tag{2}$$

where L_w (mm) is the processing length, $\triangle$(mm) is the machining allowance, n (r/min) is the spindle speed, f (mm/rev) is the feed

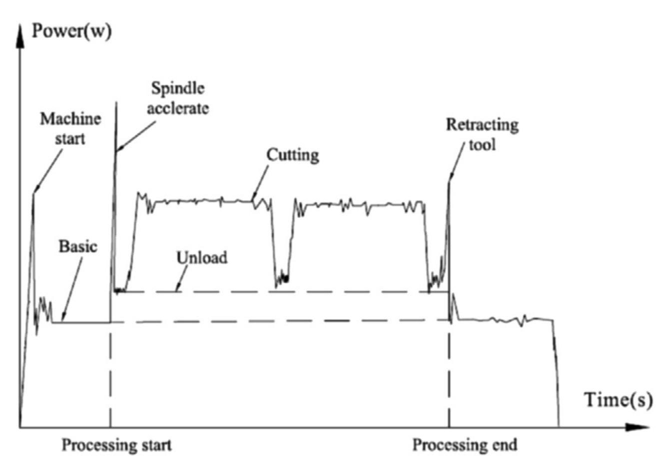

Fig. 1. The power profile of machining process of a CNC machine tool.

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