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Empirical models for specific energy consumption and optimization of cutting parameters for minimizing energy consumption during turning

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ABSTRACT

The article presents approach for optimization of cutting parameters for minimizing direct energy consumption during turning. Presented are the results of the experimental studies of the dependence of the specific energy consumption by material removal rate (MRR) when turning of steel using CNC lathes and an improved empirical model of this dependence. This model is used for the formulation of a model of direct energy consumption expressed by the cutting parameters. An equation for the optimal cutting speed is devised by applying the minimum energy criterion. The influences of the insert grade, of the feed and depth of cut on the minimum energy consumption have been found through numerical research. Recommendations for their selection have been made based on considerations for minimum energy during turning.

1. Introduction

1.1. Motivation

The constant increase of energy consumption in the world economy and the failure to provide the quantities needed as well as conditions for the utilization of new energy sources, has lead to a dramatic increase in energy costs over the last decades. Furthermore, the increased production and consumption of energy, intensifies the pollution of the environment and can eventually cause climate changes, which can lead to substantial additional costs in the future. This is why energy conservation is a topical issue for the world economy, which is the reason why the European Parliament has adopted a series of documents concerning the decrease of energy consumption of products.

The working plan of the Ecodesign Directive (Working Plan, 2008) provides a list of 10 priority product groups with a significant energy-saving potential, one of them being the group of machine tools. This group has been categorized as one with high energy consumption – higher than 10,000 PJ/y ($2.78*10^{12}$ kWh/y). A Directive of the European Parliament has been adopted concerning the indication of energy consumption and of other resources for products, connected with energy consumption, on labels (Directive, 2010). Despite the discussion concerning the necessity of evaluation of the energy consumption of machine tools (Sabastian, 2008), they will have to be classified and denoted according to their energy effectiveness in the years to come. In this regard, over the past few years, different researchers have conducted detailed energy-related studies of machine tools. In this article, studied are the specific energy consumption, models of the power and energy consumed, and the optimization of the cutting parameters with regard to the minimal consumed energy during turning on CNC turning machines. Some results, obtained by different researchers in these fields, will be discussed below.

1.2. Specific energy consumption

The study of the dependence of the specific energy consumption on the cutting conditions is needed in order to create prerequisites for the optimization of these conditions according to the criterion concerning minimal energy consumption.

For the calculation of the specific energy consumption E_{cs} during face milling of aluminum alloy, the following equation has been suggested (Draganescu et al., 2003):

$$E_{cs} = \frac{P_c}{60 \cdot \eta \cdot Z}, \ \mathrm{kWh/cm^3} \tag{1}$$

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Where, P_c is the cutting power in kW; Z is the material removal rate (MRR) in cm^3/min; η is the efficiency of the milling machine.

The cutting power is determined by the peripheral cutting force, expressed by a second degree polynomial mathematical model of the cutting parameters during milling. Such a polynomial is used to approximate the dependence between the efficiency, the moment of cutting, and the spindle speed of the milling machine. The mathematical model of the specific energy consumption based on the cutting parameters becomes too complex.

Li and Kara (2011) have suggested a model for the specific energy consumption (SEC) depending on the MRR with a simple structure.

$$SEC = C_0 + \frac{C_1}{MRR}, \tag{2}$$

where, C_0 and C_1 are specific machine coefficients.

This model is used to approximate the dependence between the specific energy consumption and MRR for several lathe and milling machines for different work materials (Kara and Li, 2011). The consumed energy during turning and milling can be predicted accurately enough through these models. The energy effectiveness of the machines can be evaluated as well. The coefficient of determination of the received models is greater than 0.90, but as the authors note, the coefficient C_1 does not correspond to the power P_0 according to the model of Gutowski et al. (2006):

$$P = P_0 + k\dot{v} \tag{3}$$

where, P is the total power in kW, P_0 is the idle power in kW, $\dot{v}$ is the rate of material processing in cm^3/s and k is constant in kJ/cm^3.

The authors explain this fact with the complex influence of different factors.

Li et al. (2013) offered an improved energy consumption model as a function of MRR and spindle speed for material removal process. For milling machine tools, the developed model could provide a more accurate energy estimation for specific milling operations compared to the model considering only MRR (Eq. (2)). There have been developed second degree polynomial mathematical models of the dependence between the consumed power and the cutting speed, feed, depth of cut, and nose radius during the turning of tool steel AISI P-2 using a CNC lathe (Aggarwal et al., 2008). The same kind of model of the consumed power related to these factors has been established during the turning of aluminum alloy 7075 (Bhushan, 2013). These models can also be used to devise respective models for the specific energy consumption with regard to the cutting parameters. However, these would have too much of a complex structure.

Experimental data about the influence of the depth of cut and the feed speed on the specific energy consumption during milling have been obtained (Dietmar and Vere, 2009), as well as data about the consumed power during the milling of aluminum depending on the depth of milling (Newman et al., 2012). However, they are presented in a graphical mode.

1.3. Models for energy consumption

Different researchers have suggested different models of the energy consumed during machining using machine tools.

Mori et al. (2011) suggest a model for the energy consumed during normal exploitation of a machine tool. This model is in the form of:

$$E = P_1 \cdot (T_1 + T_2) + P_2 \cdot T_2 + P_3 \cdot T_3 \tag{4}$$

where, P_1 is the constant power consumed during a non-cutting state, T_1 is the relevant time of the cycle, T_2 is the time of the cycle in a cutting state, P_2 is the power consumed for cutting, P_3 is the power consumed for positioning, and T_3 is the time used for this cycle.

According to Rajemi et al. (2010) the energy in single pass turning operation consists of the following components: machine setup energy, cutting energy, energy consumed during tool change, and energy to produce cutting tool per cutting edge.

By using the model of Gutowski et al. (2006) – Eq. (3), a new equation about the energy consumed in single pass turning operations is shown in Eq. (5) (Rajemi et al., 2010).

$$E = P_0\, t_1 + \left(P_0 + k\, \dot{v}\right)t_2 + P_0\, t_3\left(\frac{t_2}{T}\right) + y_E\left(\frac{t_2}{T}\right), \tag{5}$$

where, t_1 is the machine setup time, t_2 is the cutting time, t_3 is the tool change time, T is the tool life, and y_E is the energy footprint per tool cutting edge.

There has been proposed a new improved model for direct consumed electrical energy in machining which includes all the components of the energy consumed by the machine tool (Balogun and Mativenga, 2013). This particular model is the most comprehensive of all, and some of its components, as well as components from model (5) of Rajemi et al. (2010) have been used in this study for optimization of the cutting parameters when turning.

1.4. Optimization of cutting conditions

Different approaches have been offered for the optimization of cutting conditions with consideration for energy saving during machining.

Aggarwal et al. (2008) apply a response surface methodology and Taguchi's technique for optimizing power consumption in CNC turning of AISI P-20 tool steel. The effect of the cutting speed, feed rate, depth of cut, nose radius, and cutting environment (dry, wet, and cryogenic) has been experimentally tested. It has been determined that the cryogenic coolant is the most significant factor for minimum power consumption, followed by the cutting speed and the depth of cut. The effect of feed rate and nose radius were found to be insignificant compared to other factors.

Very similar results for the effect of cutting speed, feed rate, depth of cut, and nose radius on the minimization of power consumption have been achieved during the turning of Al alloy, SiC particle composites by applying a response surface methodology (Bhushan, 2013).

A new approach for the selection of optimum turning conditions based on minimum energy considerations has been offered by Rajemi et al. (2010). By using the model for energy consumption (5) and substituting the tool life in Taylor's extended equation, the condition $\partial E/\partial v = 0$ is used to formulate an equation for optimum tool life aiming minimum energy consumption:

$$T_{opt-E} = \left(\frac{1}{\alpha} - 1\right)\left(\frac{P_0\, t_3 + y_E}{P_0}\right), \tag{6}$$

where, α is the cutting speed exponent in Taylor's extended equation.

If the energy footprint per tool cutting edge y_E is not taken into consideration, as it is of no importance for the specific user who has already paid for the insert, the well-known equation for tool life for maximum production rate is obtained (Boothroyd and Knight, 2006).

Proposed a methodology based on models (5) and (6) for selecting optimum cutting parameters satisfies minimum energy