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12th Global Conference on Sustainable Manufacturing

Development of a reference part for the evaluation of energy efficiency in milling operations

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Abstract

Milling operations are commonly characterized by high energy consumptions and should be in focus for optimizations aiming at sustainable manufacturing processes. Research results show that within milling operations, especially in SME, up to 80 % of the applied milling cutters are solid end mills. The paper provides a proposal for a reference part which will allow a standardized evaluation of the energy efficiency and technical capability of solid end mills based on facts taken directly from the field of application. Therefore ten representative parts were selected from a portfolio of more than 1.000 parts out of five companies from different industry sectors. These ten parts were analytically examined regarding their geometrical features and their applied machining modes for a subsequent split up into more than 250 different weighted single components and measures. Based on a scientific recomposition of these single components and measures the reference part was developed.
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Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.
Keywords: energy efficiency; milling; solid end mills; reference part

1. Introduction

The principle of sustainability that was formulated the first time in forestry has become a normative term for the future-oriented development of mankind. Here the aim is to ensure the meet of the needs of the present without compromising the ability of future generations to meet their own needs. In a globalised world with economic, cultural and political networks, growing populations, technical progress, increased trade and the resulting raise of material and energy consumption, this general principle is of major relevance. Futhermore, regarding the economic context, companies are faced with the challenge of reacting flexibly to customer requirements and of operating as much cost-, material- and energy-efficient as possible at the same time [1].

Particularly in the European Economic Area, considering the background of rising energy costs and current political efforts for reducing CO_2 emissions, an increased importance is attached to the realization of energy-efficient machining processes. In the process chains of these industry sectors very often manufacturing processes on machine tools are applied which belong according to DIN 8580 to the main group cutting, in detail cutting with geometrical defined cutting edge [2].

Due to an annual share of a machine tool's operating costs from 21 % for electrical energy [3] there are strong efforts in science and research to increase the energy efficiency of machine tools. In the context of sustainable manufacturing the great significance of energy efficiency is exemplified by the fact that per year an average milling machine indirectly emits as much CO_2 as 10 medium-sized cars [4]. Important parameters for the consumption of electrical energy in milling operations are the drive powers of the main spindle, the feed drives, the coolant pumps and ancillary units as well as further peripheral devices. Also the tool's geometric properties such as the rake angle, the number of cutting edges, the flute angle as well as the material to be machined have an impact on the energy consumption. Consequently the energy-efficient designs of machine tools as well as the application of high-performance cutting tools play a key role for the realization of an increased energy- and CO_2-efficiency in these manufacturing processes.

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doi:10.1016/j.procir.2014.07.104

In industrial practice various types of milling cutters can be found. The most often applied of them are milling cutters with indexable inserts as well as solid end mills. Thereby milling cutters with indexable inserts are often applied in industrial high volume production but also are used for specific applications like roughing operations in small and medium-sized enterprises (SME). As current research results show are especially in SME approximately 80 % of the used milling cutters solid end mills [5]. Against this background this paper provides a proposal for a reference part which will allow a standardized evaluation of the energy efficiency and technical capability of solid end mills based on facts taken directly from the field of application. In addition an approach will be presented which allows the systematized development of further reference parts also for other metal-cutting machining processes.

2. State of the scientific knowledge and need for action

To achieve a basis for comparability between different entities inside a process a reference can be used as appropriate means. In the field of technical applications therefore commonly real parts with their specific machining tasks are used to make the engaged machines or equipment comparable with regard to their technical capability and efficiency [6]. For some time now established and standardized systems exists which are used for the assessment of energy efficiency of different energy-related products. In this context also a standardized labeling is already available e.g. for durable consumer goods. For example, there is the energy labeling of domestic appliances. Due to improved information for consumers in the form of markers or energy labels placed on the appliances the customer should be motivated to buy energy-efficient products. In this context Figure 1 shows an example of a dishwasher's energy label [7]. Beyond its informative and symbolical character the energy label contains important energy- and environment-related data – such as consumption of electrical energy and water – as well as information about functional characteristics, amongst others about the capacity, the noise emission and the drying efficiency. For the assessment these data and the subsequent determination of the energy efficiency of dishwashers, standard rinse cycles are carried out with a defined number of standardized place settings.

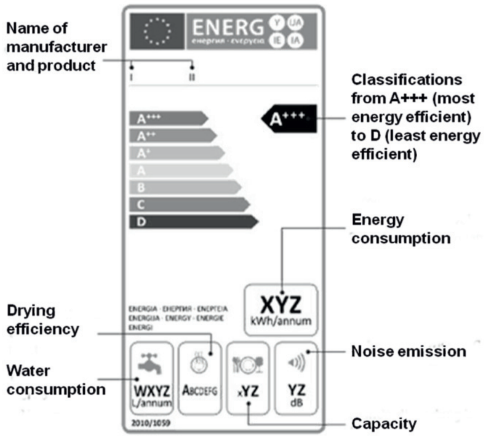

Fig. 1: Example of a dishwasher´s energy label [7]

Thereby a place setting consists of a determined number of crockery and cutlery pieces in given composition and size [8]. Even if energy labeling can already be found in many different areas of everyday life, today the industry often lacks in comparable information systems which can be used for the evaluation of the energy efficiency and technical capability of machines - especially machine tools, equipment and components. In this context the European Committee for Cooperation of the Machine Tool Industries (CECIMO) has also recognized the need for action and recently launched a self-regulatory declaration in which it set environmental standards for the machine tool industries. In this respect, the principle of sustainability and thus the optimization of the consumption of energy and other resources play an important role [9]. The following figure 2 shows two for this purpose already published proposals for reference parts which can be used for the evaluation of the energy efficiency of milling machines. In detail figure 2a shows the proposal from the Japan Machine Tool Builders' Association (JMTBA) [10] and figure 2b the proposal from Behrendt et al. [11].

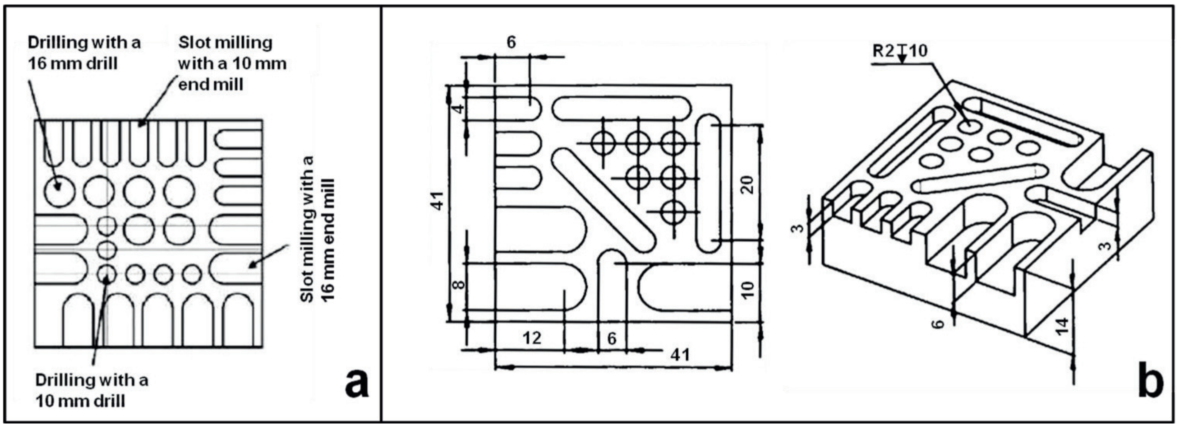

Fig. 2: (a) Reference part of the Japan Machine Tool Builders' Association [10]; (b) Reference part of Behrendt et al. [11]

For the comparative appraisal of other properties and capability characteristics of cutting machine tools various other reference parts are described in literature. For instance two company-specific reference parts are presented in [12] which are used to quantify the environmental impact of process chains in cutting manufacturing. Further reference parts are existing for 5 axis machining [13], for the evaluation of different manufacturing strategies in milling operations [14,15] as well as for the detection of the positioning accuracy and the dynamic properties of a machine tool [16].

But concerning existing reference parts often important information on the basis of development is not available. In addition there are mostly only few elements of in practice frequently appearing machining tasks contained. Thereby it becomes hard to access for users, where the geometric characteristics and the machining tasks of reference parts come from and who determined them. Nevertheless these reference parts are still suitable for specific analyses but lose explanatory power because of the lack of practical relevance and the missing of representative machining tasks from general milling operations. Regarding the field of application of solid end mills current findings from Bayreuth University's research project "Development of an energy-efficient cutting edge geometry for solid end mills" show, that in this field no standardized reference parts are existing. Carried out interviews with experts from the tool sector during the research project show, furthermore, that tool manufacturers often use self-defined test workpieces for new and further development of solid end mills, which includes only a few machining tasks such as pockets and/or steps and are in addition manufactured under optimal conditions. For the determination of performance-relevant data of solid end mills, such as tool life T and material removal rate Q simple clearing operations with constant infeed or contour parallel machining modes are commonly used. By this means the often in practice occurring machining situations with changing contact conditions, infeeds and cutting angles are only insufficiently taken into account. It can therefore be assumed that the often observed deviations between recommended cutting values and in practice really used values results thereby. As a consequence of a missing standard in the form of a reference part for this purpose, it is always only a relative comparison of solid end mills' energy efficiency and technical capability possible, which thereby depends on specific machining tasks from the user companies.

This paper introduces by analogy with the evaluation of energy and technology-relevant parameters of dishwashers by means of place settings, the development and construction of a reference part for the evaluation of the energy efficiency and technical capability of solid end mills. In addition the developed reference part can also be used to evaluate the energy efficiency of milling machines and will thereby extend already existing proposals. In this context and in analogy to the already described place settings as basis for comparison of dishwashers the introduced reference part is defined as follows: "The reference part is a determined number of geometric elements in given composition and dimension which are manufactured by defined machining modes. The reference part is usually used as basis for comparison to indicate the specific energy consumption and technical capability of solid end mills. In addition it can be used for a comparative assessment of the energy consumption of milling machines or different machining strategies."

3. Approach for the development of a reference part

3.1. Initial situation

As described in the definition above the reference part is to be used to evaluate the specific energy consumption and technical capability of solid end mills. Thereby the reference part should ensure that often occurring machining tasks from the field of application are modeled as realistically as possible. To meet this requirement the underlying parameters have to be chosen practically oriented and as closely to the field of application as possible. Thereby practice-orientation means to include expertise of tool manufacturers and user companies in the development and also to obtain traceability by choosing a less complex approach. This is especially important for the addressed sector because at the present time often a wide discrepancy between development and practical application of new methods as well as the implementation of scientific findings can be observed. Thus many scientific findings from this area of research are not implemented in practice because a wide range of users do not understand the relationships and therefore do not trust in the results [17]. From a scientific point of view traceability means that the user should be able to access the approach and the content [18]. For that purpose it is necessary to take the following criteria into account:

- Objectivity and neutrality
- Verifiability
- Reliability
- Validity
- Comprehensibility
- Relevance
- Logical argumentation [18]

To enable a wide-ranging group of users to apply the developed reference part the subsequently described approach considers the above mentioned criteria.

3.2. Approach

For the determination of the geometric shape of the reference part a classification method had to be selected, which allows to compare different parts concerning their geometric properties. For this purpose the feature technology appears to be appropriate. In general with this method all in practice occurring machining tasks can be split into features, which in turn can be manufactured by different machining modes. The feature technology represents, based on ISO 14649-10:2004(E) [19] and VDI-guideline 2218 [20], already national as well as international standards and was applied in other scientific work before (see [21, 22]). For the development of the reference part especially the geometric elements, according to the definition from ISO 14649-10:2004(E), were of interest [19]. The therein described features made it possible to split the underlying machining tasks up into features, to classify them and to make them comparable regarding to the used machining modes. In addition the existing reference parts described in chapter 2 were taken into account for the development of the reference part by also splitting them up into features. The developed schema for this approach is shown in the following figure 3.

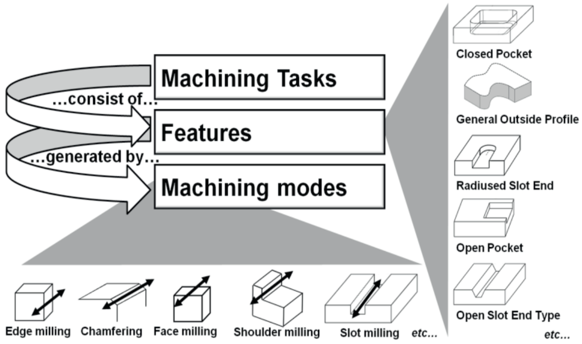

Fig. 3: Schema to split real parts up into features and machining modes

To cover the widest possible spectrum of machining tasks within the development of the reference part, consideration was given to parts of companies from the industrial sectors general engineering, tool- and mould- construction, healthcare technology, automotive and special machinery. Thereby ten representative parts with all corresponding machining tasks were selected from a portfolio of more than 1.000 parts out of the five companies from the described industry sectors. As criteria for that selection the annual production volumes as well as further specific process characteristics, such as the manufacturing processes (milling, drilling etc.) and the deployed tools, were used. Aiming at the Development of a reference part for the standardized evaluation of the energy efficiency and technical capability of solid end mills, only those machining tasks with according milling operations has been taken into account during the progress of the analyses. The documentation of important process parameters such as material removal rate Q, cutting speed v_c, number of flutes, feed rate per tooth f_z, the ratio from depth of cut and width of cut according to the tool diameter ($^{ae}/d$ and $^{ap}/d$), cooling and lubrication conditions as well as part-specific parameters such as material, dimensional and shape tolerances of features, surface roughness and part geometry completed the analyses of machining tasks for the subsequent definition of the reference part.

3.3. Evaluation of the analyses and construction of the reference part

In the first step, based on the collected data, the material for the reference part was defined. Therefore the average of the tensile strengths of all materials of the application-oriented machining tasks and of the existing reference parts was calculated based on information from technical data sheets. Here the tensile strength was considered because it substantially influences the machinability of a material. According to that, the heat-treatable steel C60E (material number 1.221) with a tensile strength of 750-1000 N/mm² [23] was defined as representative material for the reference part.

The result of the split up from all considered parts with their specific application-oriented machining tasks into features and the subsequent classification are 514 single features from 15 different feature classes. Regarding the existing reference parts 177 single features more were identified and taken into account. An excerpt from the analyses is shown in the following figure 4.

Feature	Machining mode	Tool type	Tool-Ø [mm]	n [min⁻¹]	f [mm/min]		a_e [mm]	a_p [mm]
Step	Shoulder milling	Solid end mill	16	2000	1000	...	5	12,5
Open Pocket	Shoulder milling	Solid end mill	10	1286	130	...	10	3,5
Open Slot End Type	Slot milling	Solid end mill	16	2387	439	...	16	0,3
Closed Pocket	Shoulder milling	Solid end mill	16	3395	169,75	...	16	4
⋮	⋮	⋮	⋮	⋮	⋮	...	⋮	⋮
General Outside Profile	Shoulder milling	Solid end mill	16	3396	169,8	...	12	8
Open Slot End Type	Slot milling	Solid end mill	16	5000	3000	...	16	0,1
Loop Slot End Type	Shoulder milling	Solid end mill	16	400	1200	...	8	2

Fig. 4: Excerpt from the data analysis of features

For the following construction of the new reference part a reference basis for the weighted breakdown of the feature classes had to be chosen. In this context the chipped volume of every feature class within all considered machining tasks seems to be appropriate. By using the CAD-software Pro/ENGINEER© the volume of every feature from the application-oriented machining tasks was calculated. For the existing reference parts the specific volumes were calculated based on the geometrical quantities given in the corresponding drawings. As a result of this step the overall chipped volume could be attributed to every feature class. Figure 5 gives an overview of the distribution of the ten most occurring single feature classes.

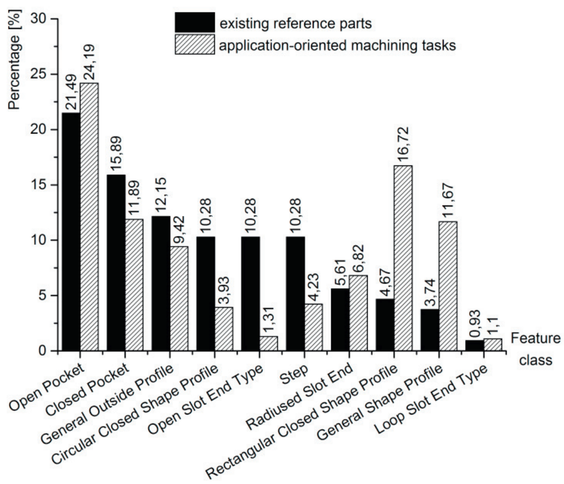

Fig. 5: Volume-based distribution of the feature classes

It can be seen that the most represented feature class “Open Pocket” takes 24,19 % of the chipped volume from all analyzed application-oriented machining tasks. Followed by “Rectangular Closed Shape Profile” with 16,72 % and “Closed Pocket” with 11,89 %. Regarding this result it is obvious that the percentages of some feature classes, which are occurring within the application-oriented machining tasks, are deviating from the percentages of the feature classes represented in existing reference parts. Especially with regards to the shown reference parts of the JMTBA (Figure 2a) and Behrendt et al. (Figure 2b) the deviation becomes apparent. So for milling operations the reference part from the JMTBA only consists of features from the feature class “Radiused Slot End”. The reference part from Behrendt et al. in addition encloses features from the feature class “Closed Pocket”. However, by considering these two feature classes, only 18,71 % of the ten most often occurring feature classes that have been identified within the research project are represented in this proposal. Taking these facts into account and using the analogy from dishwashers again (see chapter 2), it might be the same as testing dishwashers’ efficiency only by filling them with dinner plates disregarding other crockery and cutlery. These findings support the assumption that existing reference parts represent real machining situations only to a limited extend and put in evidence the novelty of the described approach at the same time.

Figure 6 shows an isometric view of the developed reference part which will allow the standardized evaluation of the energy efficiency and technical capability of solid end mills based on facts taken directly from the field of application. During the construction of the reference part the focus was set on all identified feature classes from the application-oriented machining tasks to meet the described requirements as good as possible. Therefore a baseplate in dimensions of 200 x 200 x 30 mm was defined in a first step. Afterwards the feature classes were transferred to the baseplate, depending on their specific percentage. For the CAD-construction also the CAD-software Pro/ENGINEER© was applied.

For interested scientists and users from the tool sector the associated CAD-files as well as the dimensioned drawing of the developed reference part is available online. The web-link is given in the appendix of the paper.

4. Conclusion and outlook

In summary, this paper describes the successful development of a reference part for the standardized evaluation of the energy efficiency and technical capability of solid end mills which also can be used to compare different milling machines and/or machining strategies. Here, by analogy to dishwashers, application-oriented machining tasks from different industry sectors representing real parts with their specific machining requirements. Due to the feature-based approach a realistic basis for comparison was created to make the engaged tools and machines comparable with regard to their energy efficiency as well as their technical capability. By using the developed reference part for evaluation purposes, scientists and users from the tool sector can be assured that real machining situations from various milling operations are represented. Furthermore important information on the basis of the development of the reference part is available. Thereby it becomes easy to access for users, where the geometric characteristics and the machining tasks of the developed reference parts come from and who determined them.

In addition the described approach can be transferred and subsequently be used for the development and the construction of further reference parts within related areas of application like drilling or turning. In a next step the execution of machining simulations and real machining tests will take place within the ongoing research project. Herein the direct comparison of already available cutting edge geometries of solid end mills will be conducted. Therefore the occurring process loads and cutting forces will be measured with a wireless promicron SPIKE ® sensory tool holder which allows the measurement of force and torque during the milling operations. In parallel a DoE-based optimization of the cutting edge geometry shall improve the energy efficiency and technical capability of solid end mills. In this context the development goal is a new cutting edge geometry for many cases of application which will be able to significantly increase the material removal rate. This will lead to more

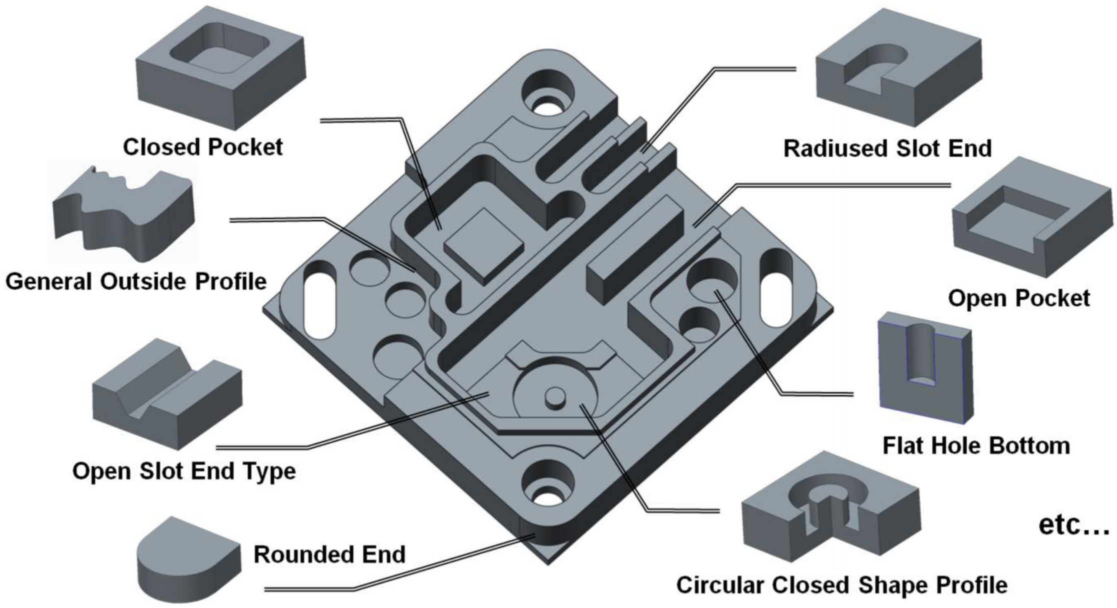

Fig. 6: Isometric view of the developed reference part with the allocation of some feature classes

energy-efficient machining operations in milling applications.

In the context of rising energy costs the evaluation of energy consumption becomes increasingly important. As part of further research works the approach presented here should be quantified economically to enable an integrated energetic and economic evaluation. Statements made by such an evaluation have high informative value because of economical and energy efficiency aspects. This will show that not at least the reduction of the energy consumption supports the economic efficiency and will thereby help to decrease the pressure of time and costs.

Acknowledgements

All topics presented in this paper are outcomes of the research project “Development of an energy-efficient cutting edge geometry for solid end mills“ (Entwicklung einer energieverbrauchsoptimierten Schneidengeometrie für Vollhartmetall-Schaftfräser). The authors would like to express their gratitude to the Bavarian Research Foundation (Bayerische Forschungsstiftung) for funding to make this research work possible.

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Appendix: Detailed information to the developed reference part

Due to the scope and scale of the developed reference part a meaningful presentation of the construction drawing with all contained information, e.g. the dimension lines, section views etc. is not possible in this paper. Interested scientists and users from the tool sector can download the CAD-models of the developed reference part as well as the construction drawing from the webpage of the research project. The data can be accessed by using the following link:
http://www.vhm-fraeser.uni-bayreuth.de/de/ergebnisse