Journal of Machine Engineering, Vol. 13, No. 4, 2013

energy consumption, planning,
technological process

Piotr RUSEK[1]
Edward WANTUCH[2]
Krzysztof ZAGÓRSKI[2]

THE PROBLEM OF ENERGY-CONSUMING PROCESSES IN THE PLANNING OF MODERN MANUFACTURING TECHNOLOGIES

Despite the application of a series of universally acknowledged procedural principles, the manufacture of elements is a process in which the skills and professional experience of the planner are of continued importance. This leads to a certain degree of subjectivity in evaluation as well as to arbitrariness and variety in the solutions presented by process engineers. By introducing evaluations of the energy consumption of processes as an additional criterion, it is possible to make planning more objective, to reduce arbitrariness in the selection of production technologies, and to reduce energy consumption and manufacturing costs. An example of the application of energy consumption indices in the design of a selected manufacturing process is given in this article.

1. INTRODUCTION

The attempt of this paper is disclose energy consumption problem in machining which became much more significant as a result of present CO_2 limitations superimposed to European Community countries and imperious necessity to spend extra money for its surplus quantities. This transforms economic conditions for manufacturing processes. Besides, problem of machining energy expenses related to the development of machine tools automatization involves certain cutting parameters modification, since manual work of operators trough automatically controlled devices was replaced.

Energy is a basic natural resource, and its acquisition is particularly important to the conduct of harmonious human productive activity. Despite the discovery of increasingly efficient energy sources on our planet and in its surroundings, the costs of energy acquisition are growing. At the same time, the development of new technologies is proceeding in the direction of increasingly energy-consuming methods enabling the implementation of new, efficient, high-quality manufacturing operations. The production

---

1 Institute of Advanced Manufacturing Technology, Cracow, Poland
2 AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Cracow, Poland,
E-mail:zagkrzys@agh.edu.pl

of new materials also requires greater amounts of energy (see Fig. 1 energy consumption of production of new and more durable engineering materials; the materials that consume the least energy are natural, such as wood). These two trends the growing cost of energy acquisition and the need to use more energy-consuming manufacturing methods which are dominant in current manufacturing technology require the application of optimization procedures in both the development of ecological (economical) production paths and the selection of the conditions for their implementation [7]. New technologies are not always harbingers of energy-saving manufacturing processes.

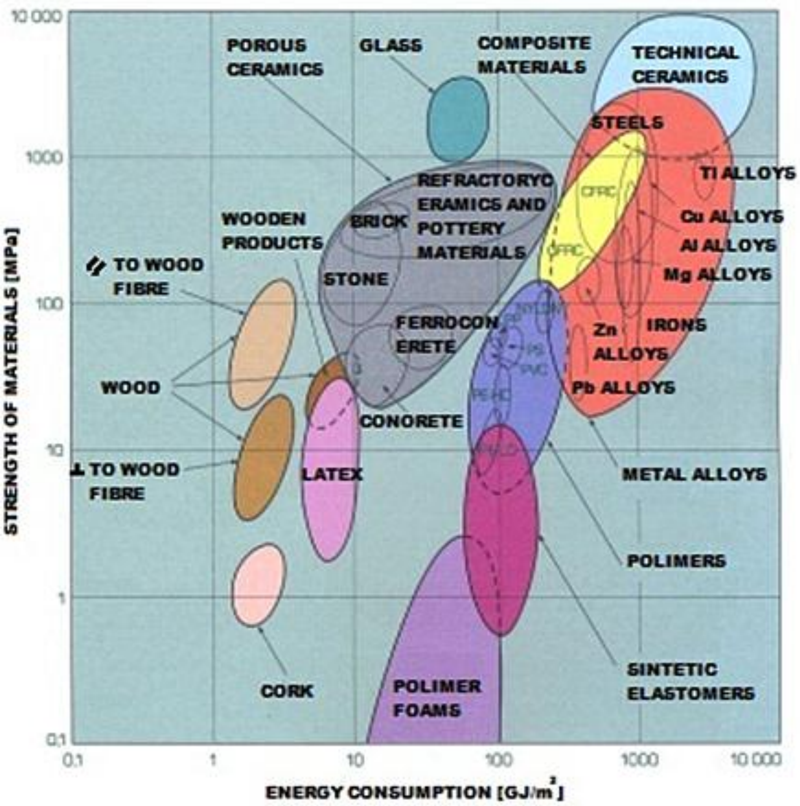

Fig. 1 Energy consumption of engineering materials according to Leszek A. Dobrzański [1]

The production of energy brings with it many side effects that can significantly impact the conditions of mankind's existence on Earth. One of these effects, which is being elevated to the rank of a global problem by numerous academic environments, is the problem of harmful CO_2 production, which accompanies industrial activity and contributes to global warming and the advance of unfavourable climate change. From the first conference devoted to the protection of mankind's natural environment, which took place in 1972 in Stockholm, to the establishment of climate protection principles as a result of the agreement of UN member states at a conference in Rio de Janeiro in 1992, the discussion concerning the impact of human activity on observable climate change on Earth has continued. Notwithstanding the inconclusive opinions of experts regarding the impact of our civilisation on climate change and particularly emissions of so-called 'greenhouse gases', particularly CO_2, into the atmosphere, in this time of growing and unlimited consumption, reflections on the impact of human industrial activity on potential climate changes are justified. The hypothesis that, in principle, everything that modern civilization has achieved in technological terms is the result of the achievements of individual branches of technology is difficult to negate. However, in the context of current climate problems, evaluation of the influence of these fields of engineering in terms of their energy consumption, on emissions of greenhouse gases into the atmosphere, among other things, is not so clear-cut. Taking into account one current opinion that treats as fraudulent the emphasis on civilisation's impact on climate change, one can cite the results of comprehensive studies of the closed circulation of the CO_2 in seas and oceans, in the atmosphere, and in the biosphere, which point to the relatively slight impact of human industrial activity on the production of this greenhouse gas [2]. Truly, on earth there are enormous sources of energy, such as thermal energy associated with the activity of the earth's interior, that produce great masses of CO_2 on which we have no influence. Theoretically, there are ways to acquire energy from the unimaginably large sources originating from natural phenomena occurring in and on the earth, such as volcanic activity, the movement of air masses and large water masses, and solar radiation, but practically, the amount of energy thus obtained, with the exception of nuclear energy and hydro energy, does not constitute a significant contribution in the earth's energy balance on a macro scale.

The acquisition of useful energy is related to significant economic and technological limitations. Because of this, in reality, the base of our energy resources is small, and only their rational management based on the principle of economical consumption (low energy consumption) and ongoing studies of the acquisition of new, cheap energy sources guarantees the world's continued sustainable economic development.

Notwithstanding the most recent findings concerning the ongoing dispute, the attempt to evaluate individual fields of engineering in terms of the energy consumption of material shaping processes, considered to be the sum of the energy consumption of individual steps, starting from the acquisition of raw materials (minerals) and ending with the finished product has a specific practical meaning for the purposes of new directions of development or the development of dual technology [3].

One of the primary objectives of sustainable manufacturing is to minimize energy consumption in its manufacturing processes. Unfortunately manufacturing efficiency research and development has always focused on technological improvements, however often at the expense of higher energy consumption [4],[5].

2. ENERGY CONSUMPTION OF PRODUCTION PROCESSES

Given the existence of many formulas and terms that enable energy-consuming industrial processes to be described, the authors have adopted the terminology introduced by [6],[8] among others, for the purposes of this article. In this sense, the *energy consumption of an operation* e_{op} will be understood as the ratio of energy expended during the performance of a given operation of an industrial process to the results of this operation. In the case of manufacturing processes, this is expressed in terms of [J/m^3] or [J/kg]. *Energy* *consumption of processing* e_p is the sum of all energy consumed in the acquisition of a semi-finished product, which is the material necessary to complete the process of manufacturing the analysed element with reference to the result of this activity (units as above). *Specific energy consumption* $e_{wł}$ is the quotient of energy expended to acquire various engineering materials and the results of this activity (units as above).

Energy of element production Q is the sum of all energy expended to manufacture a product (element) with a specific mass or volume. In the case of individual components of a technological (manufacturing) process, one can speak of *processing energy* E_p (acquisition of a semi-finished product), *coarse machining energy* E_{oz} (removal of surplus destined for coarse machining), or *finishing machining energy* E_{ow}.

$$Q = \Sigma E_i$$

where E_i is the energy of a chosen *i*-th technological operation in the process of element manufacture.

A comparison of production energies $Q_I, Q_{II}, \ldots, Q_N$ for successive variants of the analysed process, in the authors' opinion, can constitute a basis (apart from the necessity of fulfilling the technical conditions and requirements of economical production) for the final selection of manufacturing technology with regard to the minimum (optimal) process energy criterion Q_{opt},

$$Q_{opt} = \min\{Q_I, Q_{II}, \ldots, Q_N\}$$

Table 1. Energy consumption of machining for various turned materials depending on feed rate [1]

Machined material	Properties		Energy consumption of machining in MJ/m^3 for a variable feed rate [mm/rotation]			
	Strength R_m MPa	Hardness HB	0.1	0.2	0.4	0.8
Carbon steels	up to 490 490–588 Wt% 588–686 Wt% 686–834 Wt% 834–980	- - - - -	3600 4000 4200 4400 4600	2600 2900 3000 3150 3300	1900 2100 2200 2300 2400	1360 1520 1560 1640 1720
Alloyed steels	686–834 Wt% 834–980 Wt% 980–1370 Wt% 1370–1767	- - - -	4700 5000 5300 5700	3400 3600 3800 4100	2450 2600 2750 3000	1760 1850 2000 2150
Cast iron	- -	up to 200 200–250	1900 2900	1360 2080	1000 1500	720 1080
Copper Brass Bronze	- - -	- 80–120 Wt% -	2100 1600 1400	1520 1150 1000	1100 850 700	800 600 520
Aluminium Silumin Magnesium alloys	- - -	- - -	1050 1400 580	760 1000 420	550 700 300	400 520 220

Table 1 presents the typical values of the energy consumption index for machining of typical engineering materials with various feed rates. The given values can be used to calculate the energy consumption of machining processes (for example), but modern production processes are usually more complex and include such technological procedures as grinding, burnishing, erosion machining, laser machining, etc. Table 2 presents approximate values of relative energy consumption in the form of indices for certain technological operations with reference to the average operation of coarse turning.

The use of energy consumption indices, however, is not sufficient, because the evaluation of the suitability of various technological operations should incorporate a machining efficiency index.

The product of operation energy consumption index $\boldsymbol{e_{op}}$ and process efficiency V is power N_p of the production process, which, when multiplied by a unit of time (e.g. 1 second), is the unit energy necessary to carry out a given operation.

$$E_j = e_{op} \cdot \mathrm{V} \cdot t_j$$

The unit energy determined for a given operation corresponds better to production needs than the energy consumption index because it accounts for an important aspect of the efficiency of the analyzed process. This enables a better understanding of the result of the computational example included in the article, in which the use of more modern technology requires greater energy.

Another element which, once taken into account, may have significant practical meaning is the concentration (density) of applied energy. This has particular significance in processes that use a stream of energy to machine elements, where, despite the (apparently) unfavourable energy balance, the methods used are extremely efficient due to the high concentration of energy required in separation (cutting) processes.

Table 2. Relative energy consumption of manufacturing processes (approximate values, based on [3])

Type of production process	Relative energy consumption $e_{process}/e_{tz}$	
Coarse turning	e_{tz}/e_{tz}	1
Precise turning	e_{tw}/e_{tz}	2
Rolling of constructional steel	e_{pw}/e_{tz}	0.05 ÷ 0.1 (estimated values)
Die forging	e_{pk}/e_{tz}	0.15 ÷ 0.3 (estimated values)
Grinding	e_{szl}/e_{tz}	10 ÷ 15
Burnishing	e_{nag}/e_{tz}	2
Cutting with circular saw	e_{c}/e_{tz}	2
Laser cutting	e_{cl}/e_{tz}	80 ÷ 100
Electrical discharge machining	e_{er}/e_{tz}	40 ÷ 60
Plasma cutting	e_{cp}/e_{tz}	up to 200

3. COMPUTATIONAL EXAMPLE

To illustrate the proposed method, a four-stepped axle shaft was selected, as presented in a simplified manner in Fig. 2.

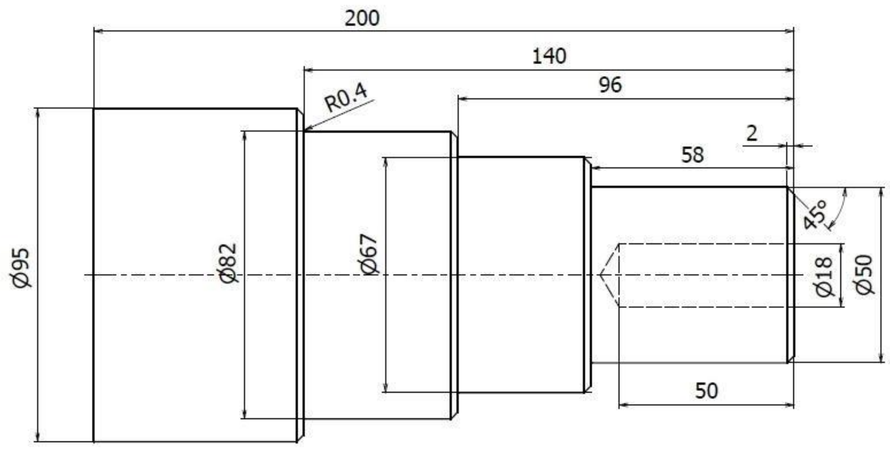

Fig. 2 Shaft

The initial material is a rod made of ST4S steel (new designation S235) with a strength of R_m = 410 MPa and diameter of 100 mm.

The production of the shaft from Fig. 2 was performed according to the following steps of the technological process:

1. Facing.
2. Coarse machining of shaft steps.
3. Finishing machining of shaft steps.
4. Execution of chamfers on individual shaft steps.
5. Execution of a center hole for the opening Ø18.
6. Execution of opening Ø18.
7. Cutting the finished shaft from the rod material.

Calculation of energy consumption was carried out for point 2 of the framework technological process (coarse machining of individual Fig. 3 shaft steps) performed on two machine tools. Table 3 presents the results of selection of machining parameters (a_p, f, v_c), calculated component machining forces: circumferential $F_c = k_c a_p f$, advance $F_f = 0.25F_c$, and resisting $0.4F_c$.

The following were calculated: machining energy $E_c = F_c v_c$, advance energy $E_f = F_f v_f$, and working energy $E_e = (E_c+E_f)t_z$ (t_z- treatment time) . Selection of parameters and calculations were made for two machine tools:

1. TUJ 50M turning lathe the cutting tool shank and cutting insert were selected for machining from the electronic catalogue of the Sandvik Coromant company: shank designated PCLNR 2525M 16, cross-section 25mm×25mm, insert designated CNMA 16 06 16-PR 4225 [10], with a thickness of 6.35 mm and radius of 1.6mm [11]. The cutting speed was determined on the basis of machine power TUJ 50M.

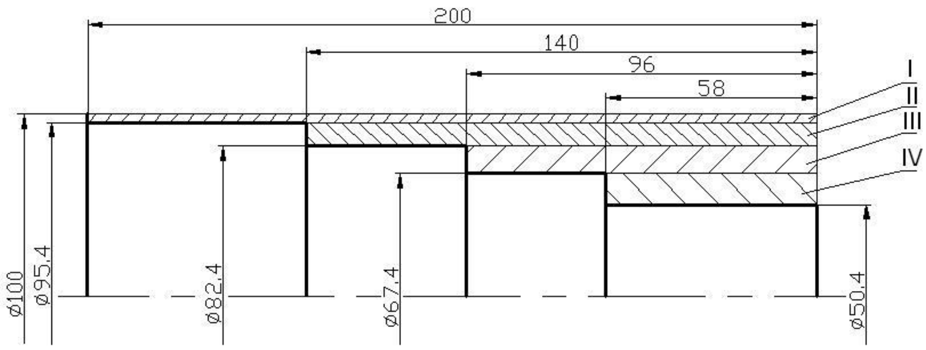

Fig. 3 Shaft coarse machining

Table 3. Values of selected machining parameters, calculated machining forces and machining energy for the TJ 50M machine tool

Shaft step	Machining parameters			Machining forces			Energy for unite time		Working energy
	a_p [mm]	f [mm/rev]	V_c [m/min]	F_c [N]	F_f [N]	F_p [N]	E_c [kJ/s]	E_f [kJ/s]	$(E_c+E_f)t_z$ [kJ]
I	2.3	1.3	110	2392	598	957	4.385	0.005	115.89
II	6.5	1.38	39	7176	1794	2870	4.665	0.006	215.80
III	7.5	1.33	35	7980	1995	3192	4.655	0.007	148.53
IV	8.5	1.18	35	8024	2006	3209	4.68	0.008	82.98
Energy required for coarse machining of all steps $E_{mach} = \Sigma E_e$									563.2

Based on machining energy, the energy stream required for the performance of the coarse machining process was calculated for the TUJ 50M turning lathe at 563.2kJ.

Table 4. Values of selected machining parameters, calculated machining forces, and machining energy for the Haas ST-20 turning station

Shaft step	Machining parameters			Machining forces			Energy for unite time		Working energy
	a_p [mm]	f [mm/obr]	V_c [m/min]	F_c [N]	F_f [N]	F_p [N]	E_c [kJ/s]	E_f [kJ/s]	$(E_c+E_f)t_z$ [kJ]
I	2.3	0.25	380	1596	399	638	10.1	0.002	400.04
II	3	0.25	380	2081	520	832	13.2	0.003	348.56
	3	0.25	380	2081	520	832	13.2	0.003	324.79
	0.5	0.25	380	347	87	139	2.2	0.0005	50.17
III	3	0.25	380	2081	520	832	13.2	0.007	206.03
	3	0.25	380	2081	520	832	13.2	0.007	191.50
	1.5	0.25	380	1041	260	416	6.5	0.002	86.47
IV	3	0.25	380	2081	520	832	13.2	0.005	101.68
	3	0.25	380	2081	520	832	13.2	0.005	92.56
	2.5	0.25	380	1734	434	694	10.9	0.004	69.02
Energy required for coarse machining of all steps $E_{mach} = \Sigma E_e$									1870.82

2. Haas ST-20 turning station the following were selected for machining from the electronic catalogue of the Sandvik company with the help of a program of the Sandvik Coromant company: *'CoroGuide version 2013.1* holder, DCLNR 2525 M16 and insert, CNMG 1606 04-QM 4225'[9]. The obtained machining parameters and calculated machining force components and working energy components are compiled in Table 4.

Based on machining energy. the energy stream required for the performance of the coarse machining process was calculated for the Haas ST-20 turning station at 1870.82 kJ.

4. GENERAL CONCLUSIONS

The performed calculations show that new technological processes that use advanced tool materials and modern production resources are characterized by greater energy consumption compared to processes using conventional machine tools. However. despite the higher energy consumption of the manufacturing process. incomparably higher quality and efficiency of machining is obtained.

Also cutting tool manufacturers doesn't optimize the process when propose certain parameters advantageous for their products but not necessarily for the whole manufacturing. (including energy consumption).

In reality. the energy consumption of new processes performed on automated computer controlled workstations is even greater. since it requires the energy consumption of auxiliary processes related to the automation of tool exchange. automation of exchange of machined objects. etc.. to be taken into account. Analysis of the energy consumption of various justifiable technological variants of procedures and operations may make evaluation of selected technology more objective. particularly when the costs of greenhouse gas emissions into the atmosphere resulting from the production of primary energy start to actually influence the national economy.

It is obvious that currently no one really care about the energy consumption of machining because the energy is relatively cheap and easy to obtain. The energy cost slowly grows and only the most energy devouring processes and technologies are pointed out and limited. However the global tendency is not to ignore facts of unjustified waste of machining energy which could be easy to save and use for other purposes.

REFERENCES

[1] DOBRZAŃSKI L. A., 2009, *Fundamentals of material design methodologies*, WPŚ, Gliwice, (in Polish).

[2] FRIEDRICH-KAR E., 2011, *Langzeit-Temperaturreihen widerlegen menschengemachten Klimawandeln,* Fusion 3.

[3] RUSEK P., WANTUCH E., ZAGÓRSKI K., 2013, *The energy consumption in manufacturing process planning,* Szkoła Obróbki Skrawaniem, 7 WPP, Poznań, (in Polish).

[4] BI Z. M., WANG L., 2012, *Optimization of machining processes from the perspective of energy consumption: A case study*. Journal of Manufacturing Systems, 31, 420– 428.

[5] SALONITIS K., BALL P., 2013, *Energy efficient manufacturing from machine tools to manufacturing systems,*

Procedia CIRP 7, 634 – 639.
[6] SALA A., 1993, *Reducing energy intensity*, Wydawnictwo:Instytut Technologii Eksploatacji, Radom, (in Polish).
[7] PAN'KOY L.A., 1997, *Ehkologischeskie aspekty abrazivnojj obrabotki*, STIN, 12.
[8] SILIN S.S,. BARANOV A.V., 1999, *Optimizacija operacijj mekchanicheskojj obrabotki po ehnergeticheskim kritrrijam*. STIN, 1.
[9] PETRUSHIN S.I., 2007, *Ehkonomicheski obosnovannyjj srok sluzhby rezhushhikh instrumentov*, Vest. Mashinost, 4.
[10] http://www.sandvik.coromant.com
[11] SILIN S.S,. BARANOV A.V., 1999, *Optimizacija operacijj mekchanicheskojj obrabotki po ehnergeticheskim kritrrijam*. STIN, 1.