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REDUCING THE ENERGY CONSUMED AND INCREASING ENERGY EFFICIENCY IN THE TURNING PROCESS

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Abstract: The rapid development of industries considerably leads to rapid and gradual changes in energy consumption. This work presents a model of energy reduction with an increased energy efficiency of the machine tool. The study focuses on the turning of 304L stainless steel. Combinations of cutting parameters are obtained using ANOVA analysis of variance. This study shows that the primary factor most influencing the total energy consumed is the feed rate with a contribution of 84.14%. Also, energy efficiency decreases with increasing material removal rate MRR. The results obtained with the simulation by the finite element method (FEM) are very close to the results obtained experimentally. In this work, it has been shown that the reduction in energy consumption can reach a value of 58.42%, and the increase in energy efficiency (EE) of the machine can reach 18.96%.

Key words: turning, ANOVA, energy efficiency, FEM, minimizing energy consumption.

1. INTRODUCTION

The main objective of industries nowadays is to minimize the cost of the products by maintaining, as much as possible, their quality level. One of the most influential parameters in the cost of such a product is energy consumption. Faced with this problem, several strategies aimed at reducing the energy consumed while maintaining superior product quality. In the field of mechanical manufacturing, machine tools consume energy that can reach critical values. So, improving the energy efficiency of machines can lead to a significant reduction of products cost. Research on reducing energy consumption is still insufficient in the face of the increasing use of energy sources. Studies by Chaoyang et al [1] show that the reduction in consumption can reach 25%. Seung et al [2] proposed an approach for predictive modeling of power consumption based on historical data collected from machine tool operations. The studies of Luoke et al [3], relate to the reduction of non-cutting energy. The results show that the reduction can reach 8.70% and 30.42% for two different cases. Lirong et al [4] used multi-objective optimization to minimize machining process time and energy consumption per unit of material removed. Rajesh's work [5] examines the effects of cutting speed, feed rate, depth of cut, and tool nose radius in turning 7075 Al wt% SiC composite. The results show that power consumption can be reduced by 13.55% and tool life, increased by 22.12%. Nikolaos et al [6] present a new approach aimed at improving the energy efficiency of machine tools through the online optimization of cutting conditions. Studies by Oda et al [7] focus on improving cutting conditions for 5-axis machine tools, in particular tool angles, and cutting speed to reduce energy consumption. Mori et al [8] develop a new method of controlling spindle acceleration to reduce power consumption. The work of Liu et al [9] proposes a new model for forecasting energy consumption in machining processes. The results show that the studied model can lead to better precision than others. The studies by Oda et al [10] describe an investigation into the reduction of energy consumed in a production line made up of several machines. The results show that the energy consumed can be reduced by about 8%, and the cycle time is reduced by 20%.

In this present work, we investigate the effects of cutting parameters on energy consumption in the turning process of 304L stainless steel. The objective is to optimize the cutting parameters to minimize energy consumption and increase the energy efficiency of the energy system.

NOMENCLATURE

N: Spindle speed (rev/min) (rpm)
V_c: Cutting speed (m/min)
a_p: Depth of cut (mm)
f: Feed rate (mm/rev)
TEC: Totale energy consumed (J)
CEC: Cutting energy consumed (J)
TPC: Total power consumed (W)
TSEC: Total specific energy consumed (J/mm^3)
CPC: Cutting power consumed (W)
NLP: No-load power (W)
EE: Energy efficiency (%)
t: Cutting time (s)
MRR: Material removal rate (mm^3/s)
Fc: Cutting force (N)

2. MATERIALS AND METHODS

2.1 Materials

The specimen used is a cylindrical part of length L = 46 mm and of diameter 58 mm. The material used is austenitic 304L stainless steel. The chemical composition of 304L stainless steel is shown in Table 1. This material has a high corrosion resistance with hardness (174 HB). It has become essential in several areas, namely medicine, surgery, aeronautics, food processing, and others.

Table 1. Chemical composition of 304 L stailess steel (wt%)

C	Mn	Si	P	S	Ni	Cr	N	Co
0.014	1.56	0.43	0.035	0.027	8.01	18.06	0.092	0.2

The turning machine used is a C11MT type (ZMM, Bulgaria) with a power of 7.5 KW. The turning operations are performed with a TMNG 16-04-08PM type tool (Sandvik Coromant, Sweden)).

2.2 Power measurement

The power consumed during a machining operation is measured by a Chauvin Arnoux F205 type wattmeter (Chauvin Arnoux, France) with jaws installed in the machine's electrical cabinet. The machining process and the work plane are shown in Figure 1.

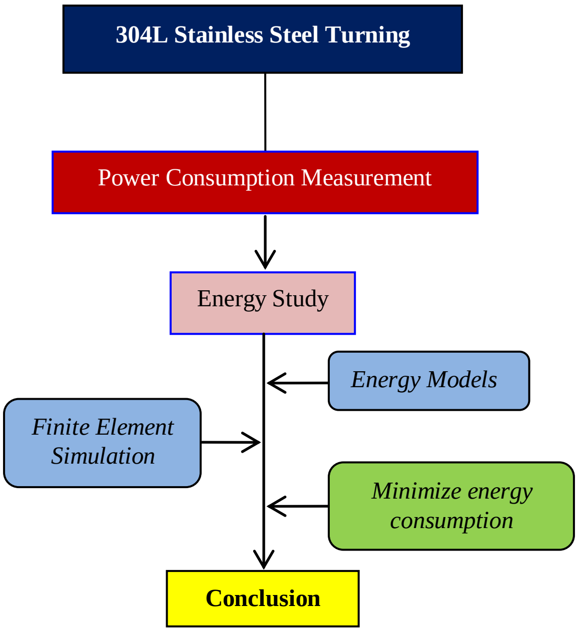


Fig. 1. Energy study plan for machining 304L steel

2.3 Planning of experiments

In this present work, the cutting parameters involved are the spindle speed (rev/min), the feed rate (mm/rev), and the depth of cut (mm). The levels of the various parameters are mentioned in Table 2.

Table 2. Cutting parameters levels

Factors	Parameters	Levels		
		-1	0	1
A	N (rev/min)	355	500	710
B	f (mm/rev)	0.05	0.075	0.1
C	ap (mm)	0.5	0.75	1

The total energy consumed is obtained as a function of the power measured for each test carried out (equation (1)). Equation (2) is used to estimate the energy during the machining process.

$$TEC = TPC \times t \tag{1}$$

However, the total power consumed TPC is defined by:

$$TPC = CPC + NLP \tag{2}$$

The cutting energy consumed (CEC) is calculated by multiplying the cutting power consumed (CPC) by the machining time t. The specific cutting energy (SCE) is determined by dividing the cutting power consumed CPC by the material removal rate (MRR). On the other hand, the total specific energy consumed (TSEC) during the material machining operation is equal to the total power consumed TPC divided by the MRR. The energy efficiency (EE) is equal to the cutting energy consumed CEC divided by the total energy consumed (TEC). Over time, the material removal rate MRR during the turning process is primarily aimed at productivity. Indeed, maximizing this parameter can have positive effects on the machining process, especially in roughing operations. The material removal rate is calculated from equation (3):

$$MRR = \frac{Vc \times f \times a_p \times 1000}{60} \tag{3}$$

In this study, the ANOVA analysis of variance was used to determine the influence of cutting parameters on the output responses. The retained results and the response surface graphs are obtained with Minitab 17.0 and Design Expert 10.0 software. Numerical finite element simulation of the cutting process is carried out with the DEFORM-3D 10.2 software.

2.4 Design with the response surface method

The use of the RSM response surface method will achieve the desired objectives of minimizing energies and maximizing the energy efficiency (EE) of the machine. Spindle speed, feed rate, and depth of cut are the input parameters for this study, and TEC, TSEC, and EE are the output responses. Fifteen experiments are used with different combinations of cutting parameters, see Table 3.

Table 3. RSM: response surface method

N°	A	B	C	**TEC** (J)	**TSEC** (J/mm^3)	**EE** %
1	-1	-1	-1	82134.00	18.19	38.27
2	-1	-1	0	88556.00	13.25	42.75
3	-1	0	1	52616.89	6.01	35.76
4	0	0	-1	39440.00	9.09	39.15
5	0	1	0	27300.00	4.25	34.07
6	0	1	1	28080.00	3.34	35.90
7	1	-1	-1	63797.50	15.33	60.26
8	1	-1	0	83401.50	13.55	69.60
9	1	0	1	40050.63	4.98	57.81
10	-1	0	-1	57687.04	14.47	41.41
11	-1	1	0	44869.50	7.62	43.50
12	-1	1	1	31265.00	4.06	18.92
13	0	-1	-1	61440.00	16.13	41.41
14	0	-1	0	77040.00	13.70	53.27
15	0	0	1	39760.00	5.41	39.64

3. RESULTS AND DISCUSSION

In this experimental study, we will acquire all the information on the effects of each combination of factors on the output responses. ANOVA analysis of variance achieves this goal by applying detailed statistical analysis to measure the rate of influence of each parameter on each response. Figure 2 shows that the total power consumed during the cutting process for a feed rate is equal to 0.05 mm/rev increases gradually with an increase in the spindle speed N and also with the depth of cut a_p.

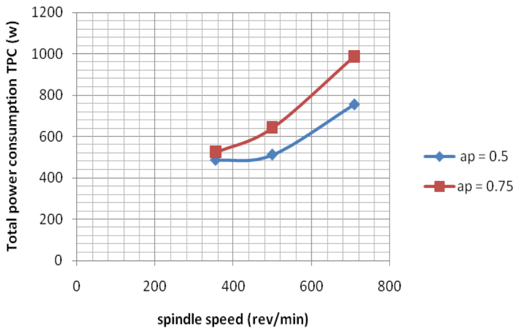
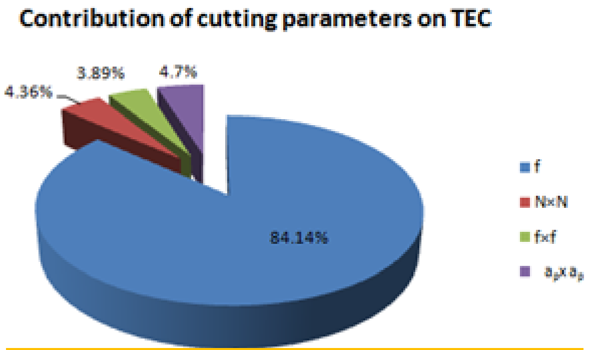


Fig. 2. Total power consumed as a function of spindle speed (rpm)

The total energy consumed TEC during the machining process is determined from equation (1) based on the total power consumed. Figure 3 shows the ANOVA analysis of variance for TEC with p-value = 0.0002, which is less than 0.05, which shows that the model is significant with a confidence interval of 97.89%. The most influencing factor on the total energy consumed is feed rate, with a contribution of 84.14%, then it comes the $a_p x a_p$ interaction with a contribution of 4.7%. Figure 4 shows that as the feed rate increases, the total energy consumed decreases, and this is due to the reduction in cutting time. From Figure 5 a), it can be seen that when the feed rate decreases, the total energy consumed increases rapidly, and this reflects the large contribution which reaches 84.14%. Similarly to the spindle speed but less than the feed rate and this caused the two parameters N and f are proportional. This result is validated by comparing with the results provided by Paramjit et al [11]. Also from Figure 5 b), we see that when the de pth of cut increases, the energy also increases but with a low amplitude, and this due to the low variation between the values of a_p.



p-value (Model) = 0.0002 ; R^2 = 97.89%

Fig. 3. ANOVA analysis of variance for TEC

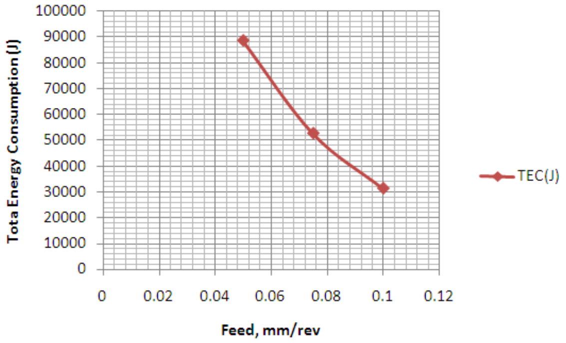


Fig. 4. Effect of feed rate on total energy consumption (TEC)

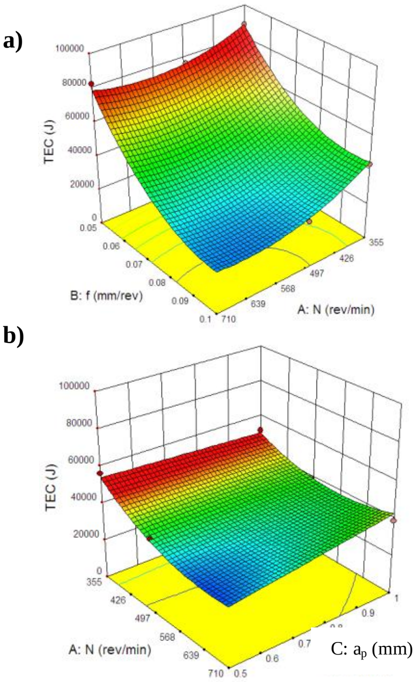
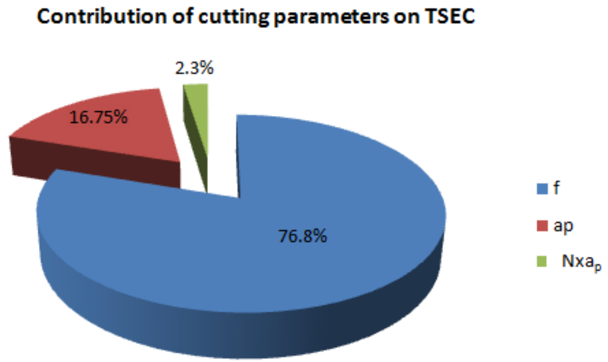


Fig. 5. 3D plots for total energy consumption (TEC)

Figure 6 shows the analysis of variance of the total specific energy consumed TSEC with p-value equal to $0.0001 < 0.05$, which means that this model is significant with a confidence interval of 98.93%. On the other hand, we note that the most influential factor on TSEC is the feed rate with a contribution of 76.8% then we find the depth of cut with 16.75%. From Figure 7 it can be seen that the minimum values of the total specific energy consumed, are obtained with high feed rate and high spindle speed. This result is similar to the results provided by Yansong et al [12] and Stefan et al [13].



p-value (Model) = 0.0001 ; $R^2 = 98.93\%$

Fig. 6. ANOVA analysis of variance for TSEC

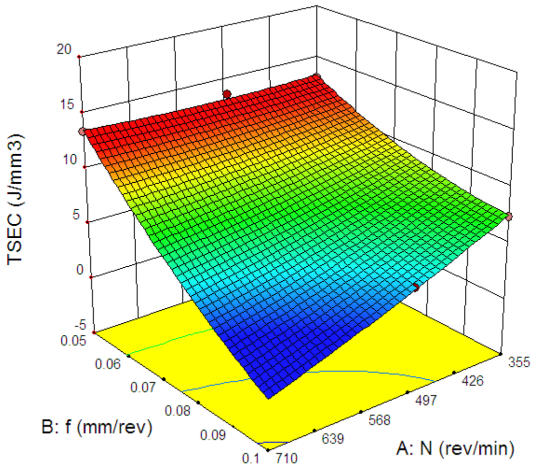
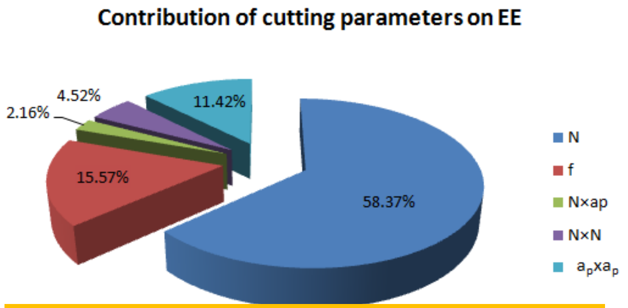


Fig. 7. 3D plots for total specific energy consumption (TSEC)

Figure 8 shows the analysis of variance of energy efficiency EE with p-value equal to $0.0078 < 0.05$, which means that this model is significant with a confidence interval of 92.25%. We can also see that the spindle speed is the most influential factor in energy efficiency with a contribution of 58.37% then it comes to the feed rate with 15.57% and the interaction $a_p \cdot a_p$ with 11.42%. Figure 9 shows that with high spindle speeds, the energy efficiency increases rapidly with low feed rates. Figure 10 shows the variation of the energy efficiency EE and the total specific energy consumed TSEC as a function of the material removal rate MRR.

We see that the energy efficiency EE increases with the increase in the material removal rate, unlike the total specific energy consumed TSEC, which decreases. This result is validated by comparison with the results provided by Cramita et al [14] and Neugebauer [15, 16].



p-value (Model) = 0.0078 ; $R^2 = 92.25\%$

Fig. 8. ANOVA analysis of variance for EE

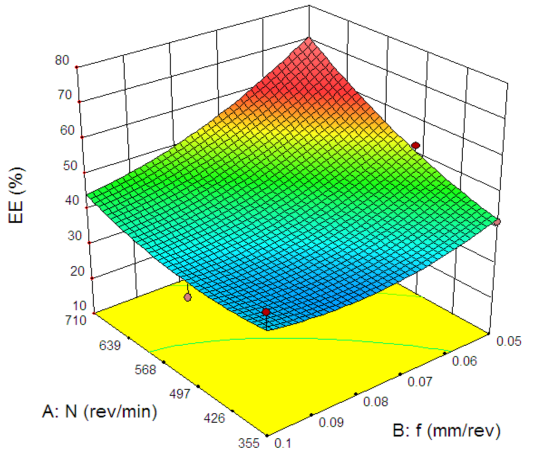


Fig. 9. 3D plots for total specific energy consumption (EE)

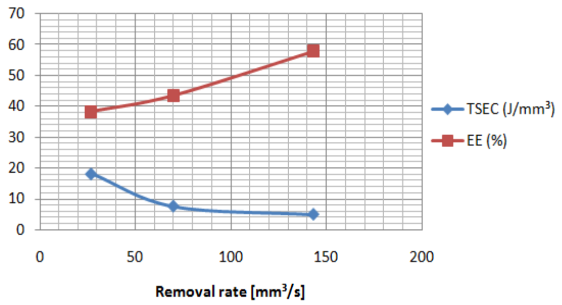


Fig. 10. Influence of the feed rate on TSEC and EE

3.1 3D simulation using the finite element method (FEM)

3D finite element simulation of 304L stainless steel turning cutting operation is performed with DEFORM 3D. The cutting length used is 5mm with a depth of cut $a_p = 0.5$mm, a feed rate f = 0.05 mm/rev and a spindle speed N = 355 rpm. These values are a combination of the cutting parameters from the first experiment. The simplified model is shown in Figure 11 with a maximum stress 1109.71 MPa. Figure 12 shows the shape of the cutting speed which is constant during the machining time which is equal to 1.08 m/s.

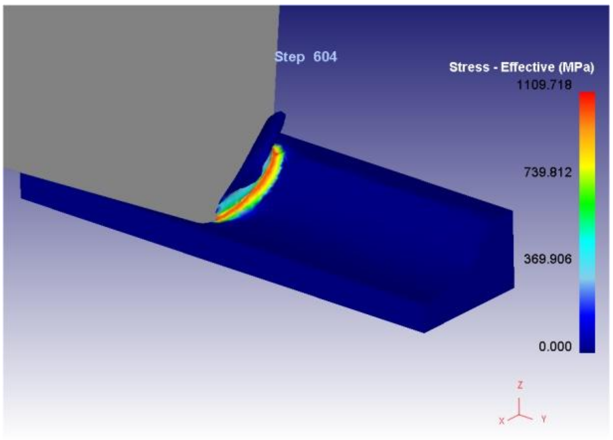


Fig. 11. Simulation of the cutting operation by FEM

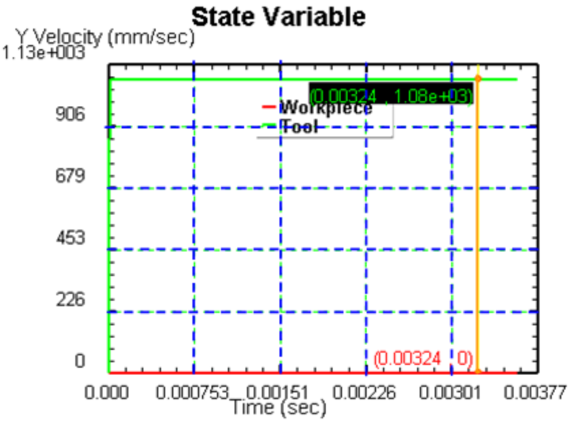


Fig. 12. Cutting speed as a function of time

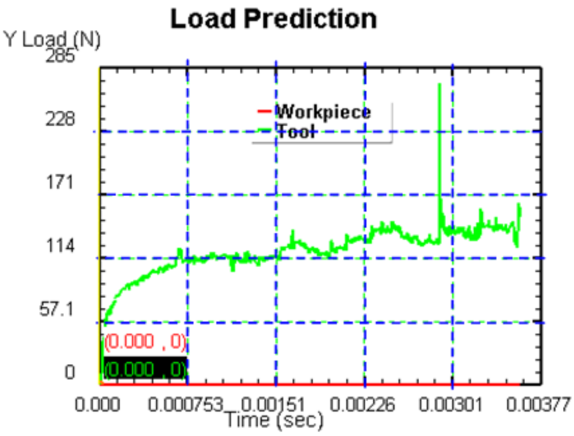


Fig. 13. The cutting force as a function of time

Figure 13 shows the shape of the cutting force as a function of time during the turning operation. All the points of the cutting force as a function of time are recorded in an Excel table, which allows us to deduce the average of the cutting force which is equal to 135.5 N.

According to equation (2) for a test (1), the total power measured is:

$$TEC(\text{measured}) = CPC(\text{measured}) + NLP(\text{measured})$$

$$= 148 + 338 = 486 \quad W$$

$$CPC(MEF) = Pc = Fc \times Vc = 135.5 \times 1.08$$

$$= 146.34W \approx CPC(\text{measured})$$

So we can conclude that the two values CPC (measured) = 148 W and CPC (MEF) = 146.34 W are close, with an error of 1.66W.

3.2 Minimize energy consumption

In this section, we will be interested in optimizing the cutting parameters using the multi-objective optimization by response surface methodology to minimize energy consumption and also increase energy efficiency (Table 4).

Table 4. Constraints for optimization of machining parameters

Condition	Goal	Lower limit	Upper limit
N (rev/min)	In range	355	710
f (mm/rev)	In range	0.05	0.1
a_p (mm)	In range	0.5	1
TEC (J)	Minimize		
EE (%)	Maximize		

The optimal cutting parameters obtained are: the spindle speed N = 710 rev/min, the feed rate f = 0.086 mm/rev and the depth of cut a_p = 0.79 mm. These values can give us a decrease in total energy consumed by 58.42% and an increase in the energy efficiency of 18.96%, see Figure 14.

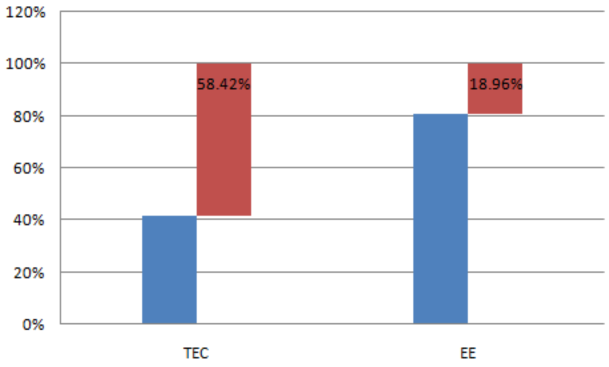


Fig. 14. Minimize energy consumption (TEC and EE)

4. CONCLUSIONS

In this work, the influence of cutting parameters (N, f, and a_p) on energy consumption and energy efficiency in the turning process of 304L stainless steel was investigated. According to the variance analysis, the feed rate is the most influential factor in the total energy consumed with a contribution of 84.14%. For energy efficiency, the spindle speed is the most influencing factor with a contribution of 58.37%, then the feed rate with 15.57%. Tests also show that energy efficiency decreases when there is an increase in the material removal rate. The studies show that the results obtained with the simulation by the finite element method are very close to the results obtained experimentally. With multi-objective optimization by the response surface methodology, one can achieve a reduction in total energy consumed by 58.42% and an increase in the energy efficiency of 18.96%.

5. REFERENCES

1. Chaoyang, Z., Pingyu, J., (2019). *Sustainability Evaluation of Process Planning for Single CNC Machine Tool under the Consideration of Energy-Efficient Control Strategies Using Random Forests*, Sustainability, **11**, 3060.
2. Seung-Jun, S., Jungyub, W., Sudarsan, R., Prita, M., (2019). *Sustainability Evaluation of Process Planning for Single CNC Machine Tool under the Consideration of Energy-Efficient Control Strategies Using Random Forests*, Sustainability, **11**, 3060.
3. Luoke, H., Ying, L., Niels, L., Renzhong, T., Jingxiang, L., Chen, P., Steve, E., (2017). *Sequencing the features to minimise the non-cutting energy consumption in machining considering the change of spindle rotation speed*, Energy, **139**, 935–946.
4. Lirong, Z., Jianfeng, L., Fangyi, L., Gamini, M., John, W., S., (2018). *Optimization Parameters for Energy Efficiency in End milling*, Procedia CIRP, **69**, 312–317.
5. Rajesh, K B., (2013). *Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites*, Journal of Cleaner Production, **39**, 242–254.
6. Nikolaos, T., Jörn, M., Jevgenijs, B., Nicolau, I, M., (2016). *Online on-board optimization of cutting parameter for energy efficient CNC milling*, Procedia CIRP, **40**, 384–389.
7. Oda, Y., Mori, M., Ogawa, K., Nishida, S., Fujishima, M., Kawamura, T., (2012). *Study of optimal cutting condition for energy efficiency improvement in ball end milling with tool-workpiece inclination*, CIRP Annals - Manufacturing Technology, **61**, 119–122.
8. Mori, M.,Fujishima, M., Inamasu, Y., Oda, Y., (2011). *A study on energy efficiency improvement for machine tools*, CIRP Annals - Manufacturing Technology, **60**, 145–148.
9. Liu, N., Zhang, Y.F., Lu, W.F., (2015). *A hybrid approach to energy consumption modelling based on cutting power: a milling case*, Journal of Cleaner Production, **104**, 264–272.
10. Oda, Y., Yoshikazu, K., Makoto, F., (2012). *Energy Consumption Reduction by Machining Process Improvement*, Procedia CIRP, **4**, 120–124.
11. Paramjit, S B., Sehijpal, S., Raman, K., (2016). *Optimization of energy consumption response parameters for turning operation using Taguchi method*, Journal of Cleaner Production, **137**, 1406–1417.
12. Yansong, G., Jef, L., Joost, D., Bert, L., (2012). *Optimization of energy consumption and surface quality in finish turning*, Procedia CIRP, **1**, 512– 517.
13. Stefan, V., Ivan, K., Krasimir, I., Simeon, G., (2014). *Empirical models for specific energy consumption and optimization of cutting parameters for minimizing energy consumption during turning*, Journal of Cleaner Production, **80**, 139–149.
14. Carmita, C-N., (2013). *Optimization of cutting parameters for minimizing energy consumption in turning of AISI 6061 T6 using Taguchi methodology and ANOVA*, Journal of Cleaner Production, **53**, 195–203.
15. Neugebauer, R., Schubert, A., Reichmann, B., Dix, M., (2011). *Influence exerted by tool properties on the energy efficiency during drilling and turning operations*, CIRP Journal of Manufacturing Science and Technology, 161–169.
16. Neugebauer, R., Drossel, W., Wertheim, R., Hochmuth, C., Dix, M., (2012). *Resource and Energy Efficiency in Machining Using HighPerformance and Hybrid Processes*, Procedia CIRP, **1**, 3–16.

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