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Article

Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force

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Abstract: Downsizing energy consumption during machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. In this paper, we propose using measured cutting force to calculate power consumption during the turning process of metals. A case study was carried out where hardened stainless steel was turned using coated carbide tool without cutting fluid. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm/rev) while other parameters were kept constant. The results indicate that energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data. This generally means cutting force can be used to calculate energy consumption during the turning of metals, provided sufficient data is available. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

Keywords: turning; cutting force; energy consumption, stainless steel

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1. Introduction

With sustainable manufacturing in mind, a product's manufacture should minimize energy consumption and negative environmental impact [1]. From the sustainable manufacturing point of view, machining is a material removal process using machine tools, where it is wasteful in its use of both material and energy [2]. Yet, given that machining can produce shapes, sizes, and surface finishes with simplicity and accuracy, it is still the most widely used manufacturing process [1,3].

Researchers have introduced models to assess environmental impact and energy consumption of machining. Munoz, et al. [4] developed modelling approaches specifically to the environmental issues of machining processes. Later on, they presented a methodology for considering environmental factors in machining facilities which used analytical process models embedded as the attributes of systems resources to determine energy use and mass flow based on process time and volume of material removed. Choi, et al. [5] developed the assessment methodology to measure the amount of the generated solid waste, the consumed energy, the incurred wastewater, and the noise level for machining processes. For energy consumption, the analytical models proposed in previous works differentiate the machine tool's energy consumption between constant and variable energy consumptions. An empirical approach was presented by Kara and Li [6] in building models for machining processes in predicting their consumed energy for each unit process. They showed that the machining process's energy consumption could be predicted using the empirical models within the set cutting parameters for the selected machine tools. Their model can calculate the energy requirement for turning or milling processes to machine a product. An on-line approach proposed by Hu et al. [7] was developed based on an energy consumption model of a machine tool for energy efficiency monitoring. Another model was proposed by He, et al. [8], seeing machining in a manufacturing system, by categorizing the machine tool's energy consumption based on the task. They found that the task flow's flexibility and variability influence the machining's energy consumption in a particular manufacturing system. These models were developed with the intention of reducing environmental impact and energy consumption when machining of metals.

Reducing energy consumption requires the capability of monitoring the machining process's energy consumption [9]. To better calculate the energy consumption, we need to incorporate the machining conditions into energy consumption. However, this is challenging considering the complexity of manufacturing systems and a large amount of data. Previous studies on this include automated monitoring and analysis of energy consumption in manufacturing systems using event stream processing techniques [9]. Another work by Rajemi et al. [10] includes optimization of the energy footprint of a machined product in developing the energy consumption model. As a case study, they machined a part by turning and analyzed the total consumed energy of the process. Afterwards, the minimum energy footprint was determined during the optimization of the total energy consumption concerning the machine tool's tool life.

We identified that many works on machining processes had reported the effect of machining parameters (e.g., speed, depth of cut, and feed) to quantitative machining responses like cutting forces, tool life, surface roughness, and cutting temperatures. The above information implies that energy consumption should also be taken into account as a machining response. In this study, we showed how to use cutting force data to approximate energy consumption. As a case study, stainless steel was turned under varying speed and feed conditions, using a carbide tool without cutting fluid. We calculated the energy consumption further and further determine the optimum machining parameters region based on the machining responses specified.

2. Cutting Forces in Turning Process

The information on cutting forces during various machining processes is essential for determining machinability. Some uses of measuring cutting forces during machining process include machining economics analysis, adaptive control applications, and numerical modelling of the machining process. As machining responses, cutting forces are studied in various machining processes. Models of cutting forces are formulated to correlate between the machining parameters to cutting forces. The empirical models are based on the established machining theory.

There are three cutting force components in the turning process, which are designated according to the direction of the cutting tool's relative movement to the workpiece (Fig. 1). First is the cutting force or tangential force (F_c), in the direction of the main cutting action. Other force components are the radial force (F_r) and the feed force (F_f) components [12,13].

During the turning process, power consumption can be an indicator of tool conditions and as a design criterion of the machining input. To determine the power consumption, commonly only the cutting force is considered. It can be calculated by (Equation 1):

$$P_c = V_c \,.\, F_c \tag{1}$$

where P_c is the power consumption (W), V_c is the cutting speed (m/min), and F_c is the main cutting force (Newton). Here, power is mainly consumed to shear the metal in the shear zone and due to tool-chip interaction or friction on the tool's rake face.

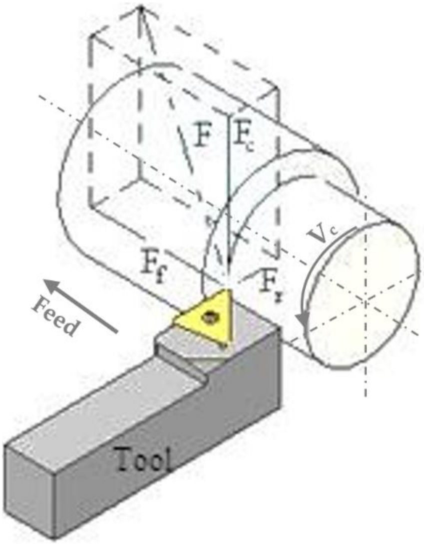

Figure 1. Cutting force components in the turning process

3. Energy Consumption

Studies on determining machining process's energy consumption commonly differentiate the energy consumption in the idle, run-time, and production modes [9,10]. Idle mode is when the machine is ready for or in between machining. Although no material removal action is performed, there is still constant energy consumption in standby mode (for example, for the operation panel and fans). Run-time mode is when the auxiliaries are on (e.g., motor for the spindle and pump for the cutting fluid) but there is no material removal action. This consumes constant energy. Production mode is when the material removal action occurs. It varies and depends on the applied load towards the machine.

Factors that affect energy consumption include cutting parameters, cutting tools, and workpiece material [14-16]. Studies found that compared to the total energy consumption, the energy consumption during production mode where material removal action occurs is small [17,18] Considering this, efforts to lower energy consumption are focused more on reducing the constant energy. Some approaches include specific components improvement or overall cycle time reduction [5,19].

We agree with the approach proposed in a previous study that the total energy consumption (E) for the turning process is a summation of the energy consumption during setup (E_1), when performing material removal (E_2), for tool change (E_3), to fabricate the cutting tool (with all its cutting edges) (E_4) and in the manufacture of the workpiece material (E_5). Considering that the workpiece material is given depending on the product and the machine shop has limited control over the energy contained in the particular workpiece material, this factor can be omitted during the machining process itself.

From the above, for the turning process, the total energy can be calculated as Equation 2.

$$E = E_1 + E_2 + E_3 + E_4 \tag{2}$$

where E_1 is the energy used during machine setup. It can be calculated as a product of the setup time and the corresponding power consumption, as shown in Equation 3.

$$E_1 = P_0\, t_1 \tag{3}$$

where P_0 is the power (W) in idle and run-time modes and t_1 is the time (s) required for machine setup.

E_2 is the machining energy consumption. It is calculated by multiplying the actual machining time by the corresponding energy consumption (Equation 4) [14].

$$E_2 = (P_0 + k \cdot \dot{v})\ t_2 \tag{4}$$

where k is specific machining energy (Ws/mm^3), $\dot{v}$ is material removal rate (mm^3/s) and t_2 is the accumulated material removal time of the turning process (s). The value for specific machining energy k can refer to [20]. Considering Equation 1, the calculation for E_2 can also be done by using P_c which is the power of the machine tool, and acknowledging that t_2 is t_c which is the actual cutting time [21,22], making Equation 5.

$$E_2 = (P_o + P_c) \cdot t_c \tag{5}$$

Thus, the equation for machining energy consumption becomes Equation 6.

$$E_2 = (P_o + F_c \cdot V_c) \cdot t_2 \tag{6}$$

E_3 is the energy used during the replacement of a tool and is calculated as a product of the time required for tool changes and the associated power. In the turning process, tool replacement is conducted manually or using automated tool changer, both of which occur when the tool is retracted away from the workpiece. Thus, it can be assumed that the energy used during the replacement of tool is as much as the power when the machine is in no-load position, which is.

$$E_3 = P_0\ t_3 \left(\frac{t_2}{T}\right) \tag{7}$$

where t_3 is the time for a replacement tool (s) and T is tool life (s).

E_4 can be calculated as the sum of energy consumed to fabricate each cutting edge (y_E) on a cutting tool. Note that cutting tools in the form of indexable inserts usually have multiple cutting edges. So, this energy should be divided by number of edges needed to perform the turning process.

$$E_4 = y_E \left(\frac{t_2}{T}\right) \tag{8}$$

y_E can be obtained from the total energy per insert (MJ) for material and manufacturing process and that refer to [20].

Based on the description above, the equation to calculate the energy consumed in a turning process can be written as Equation 9.

$$E = P_0\ t_1 + (P_o + F_c \cdot V_c) \cdot t_2 + P_0\ t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right) \tag{9}$$

or as Equation 10.

$$E = P_0\ t_1 + (P_0 + k\dot{v})\ t_2 + P_0\ t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right) \tag{10}$$

Based on both Equations 9 and 10, the total energy consumption is only distinguished in the calculation of energy during actual cutting process (E_2), which is categorized as the variable factor. Other factors, i.e., E_1, E_3, and E_4 are the same for both Equations 9 and 10, and are considered as constant factors in energy consumption calculation [6].

4. Case Study

4.1. Experimental

As a case study, previous experiment [23] is referred. Briefly, it is a turning process using a two-axes CNC lathe machine with varied cutting speed of 100, 130 and 170 m/min, with varied feed of 0.1, 0.125 and 0.16 mm/rev, and with constant depth of cut of

0.4 mm. The turning process was performed dry (without any cutting fluid). The workpiece material was an AISI 420 martensitic stainless steel (ASSAB Steel). The stainless steel was hardened throughout by heat treatment to reach a hardness value of 47 – 48 HRC [23]. The cutting tool used for the experiment was a TiAlN coated carbide tool (Kennametal) that is designated as CNMG 120408. The tool life criteria were at a maximum of 0.14 mm of flank wear width or severely damaged cutting tool.

The experiments measured the cutting force elements in all three directions (F_c, F_r, and F_f as the schematic layout below (Figure 2). A three-component turning dynamometer (Kistler, Type 9265B) with data acquisition software was used for this purpose.

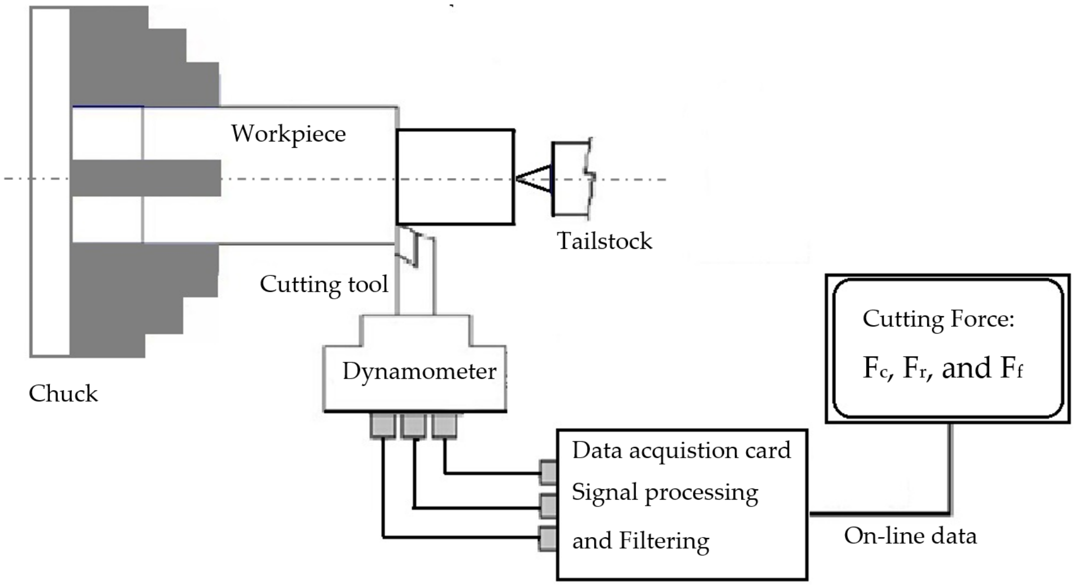

Figure 2. Schematic layout of cutting force setup

4.2.Experimental Design

Response Surface Methodology (RSM) was chosen for the design of experiments. A commercial software (Design Expert, Stat Ease Inc.) was used for this purpose. For the RSM, regression is used to approximate the machining response based on relationship between one or more factor (input variable) and the estimated response, y_{est}. Fitting of the model equation was using least square technique through residual error minimization. The model equation and its coefficients were tested for statistical significance. Analysis of variance (ANOVA) was used for this purpose. For the case at hand, a three-level factorial design having two input factors and 2 center points was applied, making 11 runs in total (Table 1). The type 1 error (α) value was set at 0.05 for the models and its coefficients to be considered as significant.

Table 1. Factor and levels for the experiments.

Factor	**Coded form**		
	-1	**0**	**1**
x_1 – cutting speed (m/min)	100	130	170
x_2 – feed (mm/rev)	0.10	0.125	0.16

5. Results and Discussion

5.1. Surface Roughness and Tool Life

The experimental results for surface roughness and tool life for all eleven trials are summarized in Table 2 [23].

Table 2. Experimental results for surface roughness and tool life.

No.	*Vc(m/min)*	*f(mm/rev)*	*Ra (µm)*	*T (min)*
1	100	0.10	0.60	30.50
2	130	0.10	0.54	8.84
3	170	0.10	0.47	3.93
4	100	0.125	0.87	19.20
5	130	0.125	0.73	5.50
6	170	0.125	0.50	3.90
7	100	0.16	0.92	15.00
8	130	0.16	0.78	4.65
9	170	0.16	0.74	2.50
10	130	0.125	0.42	5.18
11	130	0.125	0.68	7.00

Based on the results of surface roughness and tool life, selection of models using regression calculations were made [24]. The linear model was chosen for modelling the surface roughness while the quadratic model was most suitable for the tool life. The backward elimination procedure was seleccted to automatically reduce the terms that are not significant and the resulting ANOVA table for the reduced linear model for surface roughness and the reduced quadratic model for tool life is displayed in Table 3 [23].

Table 3. Result of ANOVA table for tool life and surface roughness.

Source	Sum of squares	DF	Mean square	F Value	Prob > F
Surface roughness					
Model	0.19	2	0.095	8.94	0.009
x_1	0.07	1	0.07	6.80	0.031
x_2	0.12	1	0.12	11.13	0.010
Residual	0.09	8	0.01		
Cor Total	0.28	10			
Tool Life					
Model	5.73	3	1.91	104.00	<0.001
x_1	4.92	1	4.92	267.93	<0.001
x_2	0.53	1	0.53	28.99	0.001
x_1^2	0.57	1	0.57	31.27	0.008
Residual	0.13	7	0.018		
Cor Total	5.86	10			

The final equation, in terms of actual factors, acquired from the model for surface roughness is as in Equation 11.

$$Ra = 0.4793 – 0.0031*V_c + 4.6513*f \quad (11)$$

where *Ra* is surface roughness (μm), V_c *is* cutting speed (m/min) and *f* is feed (mm/rev).

Based on the Box-Cox plot, the Log transformation is recommended based on the best lambda value found at the minimum point of the curve generated by the natural log of the sum of squares of the residuals. The final equation, in terms of actual factors, achieved from the model for tool life can be expressed as in Equation 12.

$$Ln\ T = 13.4177 – 0.1297*V_c – 9.8739*f + 0.0004*V_c^2 \quad (12)$$

where *T* is tool life (min) and the other variables were as defined previously.

5.2. Cutting Force

Based on the experiments that have been conducted, the resultant cutting force is as shown in Fig. 3.

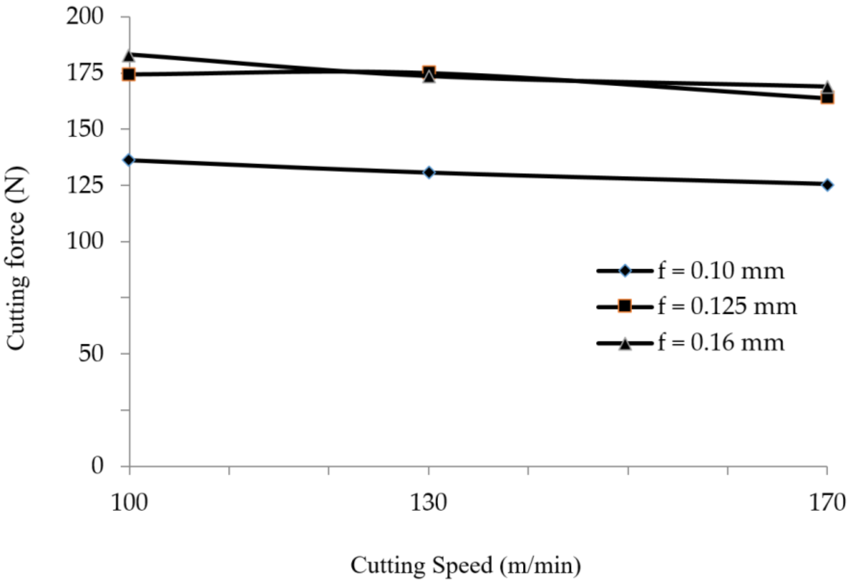

Figure 3. Cutting force at various cutting speeds and feeds

The model selection and its subsequent reduction as well as the empirical equation development for cutting force were performed in the same manner as those for surface roughness and tool life [23, 25]. The resulting ANOVA table is as shown in Table 4.

Table 4. Result of ANOVA for cutting force F_c

Source	Sum of square	DF	Mean Square	F Value	Prob>F
Model	3988.78	3	1329.59	134.33	<0.001
x_1	205.99	1	205.99	20.81	0.003
x_2	594.82	1	594.82	60.10	<0.001
x_2^2	1154.27	1	1154.27	116.62	<0.001
Residual	69.29	7	9.90		

Cor Total	4058.06	10

The final equation obtained from the model for cutting force can be expressed in terms of actual factors as in Equation 13.

$$F_C = -299.88 - 0.17*V_c + 6895.59*f - 23667.19*f^2 \quad (13)$$

where F_C is cutting force (N).

The final model equation for cutting force can be shown as a 3D contour graph (Figure 4). From Equation 13 and Figure 4, it can be observed that cutting force is affected significantly first by the feed and second by the cutting speed. Generally, feed is proportional to cutting force [23, 26].

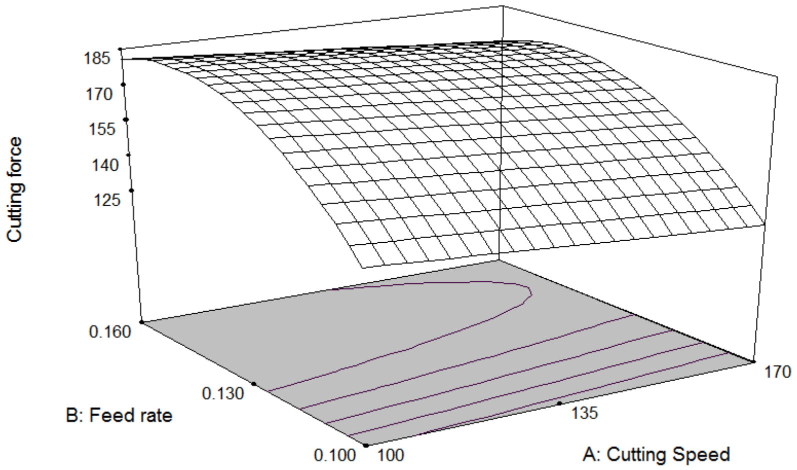

Figure 4. Response surface graph of 3D surface for F_C

5.3. Energy Consumption

The maximum energy for the turning process (E_2) was calculated using cutting force data, as in Equation 9. The maximum energy for the turning process, E_2, of 417.11 kWs was shown by the lowest of cutting speed and feed, while the minimum energy for the machining process (73.8kWs) for cutting speed and feed rate is high (Figure 5).

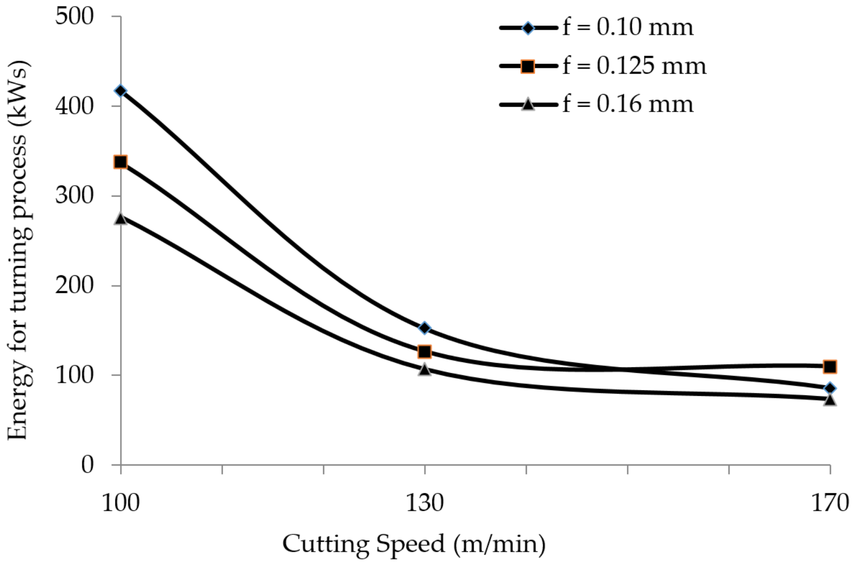

Figure 5 Energy for turning process (E_2) at various cutting speed and feed

Quadratic model was chosen to represent the data of E_2, because it has the least probabilistic value, and Prob>F. ANOVA of the selected regression model and its coefficients was performed (Table 5).

Table 5 ANOVA for machining energy consumption (E_2)

Source	Sum of square	DF	Mean Square	F Value	Prob>F
Model	130900.00	4	32715.34	98.39	<0.001
x_1	93449.15	1	93449.15	281.05	<0.001
x_2	5854.92	1	5854.92	17.61	0.006
x_1^2	35360.36	1	35360.36	106.35	<0.001
$x_1 x_2$	3578.67	1	3578.67	10.76	0.017
Residual	1994.99	6	332.50		
Cor Total	132900.00	10			

The final equation obtained from the machining energy consumption can be expressed in terms of actual factors as in Equation 14.

$$E_2 = 2949.55 - 33.00 * V_c - 4851.99 * f + 0.0954 * V_c^2 + 28.26 * V_c * f \quad (14)$$

where E_2 is machining energy consumption (kWs).

Equation 14 shows that the lower machining energy (E_2) can be obtained by choosing higher feed and cutting speed. This result is consistent with previous study that mentioned that cutting speed and feed increase reduces the power consumption [27]. In addition, it was also reported that feed is inversely proportional to the machining energy [18]. However, the surface roughness also increases when the feed is increased. This means there is a contradicting responses obtained from a machining parameter.

5.4.Optimun Cutting Parameters for the Case Study

Having all empirical models for surface roughness, tool life, cutting force and machining energy consumption; optimization can be performed to determine the suitable cutting parameters that result in preferred machining responses. Some things to consider related to machining responses are:

- hard turning as a final operation must produce smooth surface finish to meet customer demand for the geometric accuracy of machined components
- the machine shop would prefer the cutting tools to last longer
- cutting force should be low to minimize damage on machined surface, and
- energy consumption should be minimized for each workpiece volume removed.

As mentioned above, some machining responses require contradicting cutting parameter settings. Therefore, a compromise solution is necessary to select the cutting parameters. Arbitrarily, it was preferred that the surface roughness produced should be less than 0.65 μm, the coated carbide tools should last at least six minutes, the cutting force should be less than 163 N, and the machining energy consumption (E_2) is less than 280 kWs. Based on Equations 11 – 14 and plotting them on an overlay plot, these preferences will be fulfilled when cutting speed and feed combinations are in grey region (Figure 6).

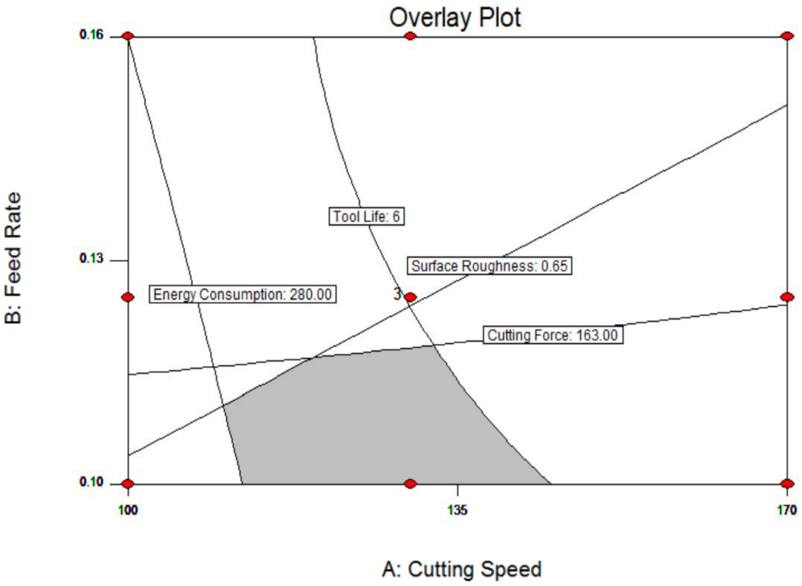

Figure 6. Overlay plot of the predetermined response criteria of T not less than 6 min, and Ra, F_C and E_2 of not more than 0.65 μm, 163 N and 280 kWs, respectively.

6. Conclusions

This study shows how to use cutting force data to approximate the energy consumption of a turning process. A case study on the turning process of hardened stainless steel (47 – 48 HRC) using carbide tool without cutting fluid was carried out. The turning process varied the cutting speed and feed. Energy consumption as a function of cutting speed and feed was obtained. Further, analysis to optimize machining parameters for the particular machining, based on machining responses including energy for actual turning process was conducted. Range of cutting speed and feed that will result in low surface roughness, long tool life, low turning process energy consumption and low cutting force was able to be determined within the scope of the case study.

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Politeknik Negeri Ujung Pandang

Rusdi Nur <rusdinur@poliupg.ac.id>

[Metals] Manuscript ID: metals-1097568 - Assistant Editor Assigned

3 pesan

Aaron Han <aaron.han@mdpi.com> 19 Januari 2021 10.21
Balas Ke: aaron.han@mdpi.com
Kepada: Denni Kurniawan <denni.kurniawan@utb.edu.bn>
Cc: Aaron Han <aaron.han@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>, Metals Editorial Office <metals@mdpi.com>

Dear Dr. Kurniawan,

Your manuscript has been assigned to Aaron Han for further processing who will act as a point of contact for any questions related to your paper.

Journal: Metals
Manuscript ID: metals-1097568
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors: Rusdi Nur , M. Y. Noordin *, S. Izman , Fethma M Nor , Denni Kurniawan *

Received: 18 January 2021
E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn

You can find it here:
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Best regards,
Aaron Han, M.Sc.
Assistant Editor
Email: aaron.han@mdpi.com

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http://www.mdpi.com/journal/metals/

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aaron.han@mdpi.com <aaron.han@mdpi.com> 19 Januari 2021 11.09
Kepada: Denni Kurniawan <denni.kurniawan@utb.edu.bn>
Cc: metals@mdpi.com, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Dr. Kurniawan,

Thank you for your submission to Metals.

We noticed that many figures in your manuscript are editable. The editable figures may cause some mistakes. Please carefully check it and change the figures to non-editable. For example, there are many text boxes in the Figure2, and the text boxes can be moved easily. Please make sure the text boxes and the figure is whole.

Thank you for your cooperation and look forward hearing from you soon.

Kind regards,
Mr. Aaron Han
Assistant Editor

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[Kutipan teks disembunyikan]

Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 19 Januari 2021 11.48
Kepada: "aaron.han@mdpi.com" <aaron.han@mdpi.com>
Cc: "metals@mdpi.com" <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Mr Han,

Thank you for the email.
Attached is the manuscript with non-editable images.

Best wishes,
Denni

[Kutipan teks disembunyikan]

Metals_Nur et al 2020-as submitted.docx
1055K

Rusdi Nur <rusdinur@poliupg.ac.id>

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metals-1097568-response to Reviewers' comments - Undangan untuk mengedit

1 pesan

Denni Kurniawan (via Google Spreadsheet) <denniutb@gmail.com> 29 Januari 2021 06.20
Balas Ke: Denni Kurniawan <denniutb@gmail.com>
Kepada: rusdinur@poliupg.ac.id
Cc: fethmamnor@gmail.com, izman@utm.my, noordin@mail.fkm.utm.my

denniutb@gmail.com telah mengundang Anda untuk **mengedit** spreadsheet berikut:

metals-1097568-response to Reviewers' comments

Assalam Profs and Drs,
Our manuscript submitted to Metals requires major revision, due 5 Feb 2021. Considering the comments and revisions required, and only limited time provided, it seems better to collaboratively work on addressing the comments. Feel free to directly write down your answers, or put it into comments on the file. Thank you in advance.

Buka di Spreadsheet

denniutb@gmail.com di luar organisasi Anda.

Rusdi Nur <rusdinur@poliupg.ac.id>

[Metals] Manuscript ID: metals-1097568 - Major Revisions Due Date 2 February

3 pesan

Metals Editorial Office <metals@mdpi.com> 28 Januari 2021 14.57
Balas Ke: aaron.han@mdpi.com
Kepada: Denni Kurniawan <denni.kurniawan@utb.edu.bn>
Cc: Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>, Metals Editorial Office <metals@mdpi.com>

Dear Dr. Kurniawan,

Thank you for submitting the following manuscript to Metals:

Manuscript ID: metals-1097568
Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors: Rusdi Nur, M. Y. Noordin *, S. Izman, Fethma M Nor, Denni Kurniawan *
Received: 18 January 2021
E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn

It has been reviewed by experts in the field and we request that you make major revisions before it is processed further. Please find your manuscript and the review reports at the following link:
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Please note that we may receive additional two review reports within 2 days. Once we received the additional reports, we will inform you immediately.

Your co-authors can also view this link if they have an account in our submission system using the e-mail address in this message.

Please revise the manuscript according to the reviewers' comments and upload the revised file within 5 days. Use the version of your manuscript found at the above link for your revisions, as the editorial office may have made formatting changes to your original submission. Any revisions should be clearly highlighted, for example using the "Track Changes" function in Microsoft Word, so that changes are easily visible to the editors and reviewers. Please provide a cover letter to explain point-by-point the details of the revisions in the manuscript and your responses to the reviewers' comments. Please include in your rebuttal if you found it impossible to address certain comments. The revised version will be inspected by the editors and reviewers. Please detail the revisions that have been made, citing the line number and exact change, so that the editor can check the changes expeditiously. Simple statements like ‘done’ or ‘revised as requested’ will not be accepted unless the change is simply a typographical error.

Please carefully read the guidelines outlined in the 'Instructions for Authors' on the journal website https://www.mdpi.com/journal/metals/instructions and ensure that your manuscript resubmission adheres to these guidelines. In particular, please ensure that abbreviations have been defined in parentheses the first time they appear in the abstract, main text, and in figure or table captions; citations within the text are in the correct format; references at the end of the text are in the correct format; figures and/or tables are placed at appropriate positions within the text and are of suitable quality; tables are prepared in MS Word table format, not as images; and permission has been obtained and there are no copyright issues.

If the reviewers have suggested that your manuscript should undergo extensive English editing, please have the English in the manuscript thoroughly checked and edited for language and form. Alternatively, MDPI provides an English editing service checking grammar, spelling, punctuation and some improvement of style where necessary for an additional charge (extensive re-writing is not included), see details at https://www.mdpi.com/authors/english.

Do not hesitate to contact us if you have any questions regarding the revision of your manuscript or if you need more time. We look forward to hearing from you soon.

Kind regards,
Aaron Han, M.Sc.
Assistant Editor
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aaron.han@mdpi.com <aaron.han@mdpi.com> 2 Februari 2021 09.11
Kepada: Denni Kurniawan <denni.kurniawan@utb.edu.bn>
Cc: metals@mdpi.com, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Dr. Kurniawan,

Please note that we just received the 3rd review report. And there won't be more reports anymore. Please revise the manuscript according to all the 3 reports.

Kind regards,
Mr. Aaron Han
Assistant Editor

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aaron.han@mdpi.com <aaron.han@mdpi.com> 4 Februari 2021 09.31
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Dear Dr. Kurniawan,

We sent a revision request for the following manuscript on 28 January 2021.

Manuscript ID: metals-1097568

Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force

May we kindly ask you to update us on the progress of your revisions? If you have finished your revisions, please upload the revised version together with your responses to the reviewers as soon as possible.

You can upload your manuscript and responses at this link:
https://susy.mdpi.com/user/manuscripts/resubmit/9510c9a5400e15da5467995875d9dbab

Thank you in advance for your kind cooperation and we look forward to hearing from you soon.

Kind regards,
Aaron Han, M.Sc.
Assistant Editor
Email: aaron.han@mdpi.com

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On 2021/1/28 14:57, Metals Editorial Office wrote:
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Journal	Metals (https://www.mdpi.com/journal/metals) (ISSN 2075-4701)
Manuscript ID	metals-1097568
Type	Article
Number of Pages	11
Title	Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors	Rusdi Nur , M. Y. Noordin * , S. Izman , Fethma M Nor , Denni Kurniawan *
Abstract	Downsizing energy consumption during machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. In this paper, we propose using measured cutting force to calculate power consumption during the turning process of metals. A case study was carried out where hardened stainless steel was turned using coated carbide tool without cutting fluid. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm/rev) while other parameters were kept constant. The results indicate that energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data. This generally means cutting force can be used to calculate energy consumption during the turning of metals, provided sufficient data is available. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

The coverletter for this review report has been saved in the database. You can safely close this window.

Authors' Responses to Reviewer's Comments (Reviewer 1)

Author's Notes	Thank you for the comments. We compiled the responses in attached file.
Author's Notes File	Report Notes (/user/review/displayFile/16116726/9UWSO6Dd?file=author-coverletter&report=10455096)

Review Report Form

English	( ) Extensive editing of English language and style required

language and style

( ) Moderate English changes required
(x) English language and style are fine/minor spell check required
( ) I don't feel qualified to judge about the English language and style

	Yes	Can be improved	Must be improved	Not applicable
Does the introduction provide sufficient background and include all relevant references?	( )	( )	(x)	( )
Is the research design appropriate?	(x)	( )	( )	( )
Are the methods adequately described?	( )	( )	(x)	( )
Are the results clearly presented?	( )	( )	(x)	( )
Are the conclusions supported by the results?	( )	(x)	( )	( )

Comments and Suggestions for Authors

Reviewed article is interesting and write at proper scientific level. Presentation method is good and mostly in accordance with generally accepted standards in that area. Below are listed some substantive remarks that have to be taken into consideration by the Authors to improve reviewed text:

the abstract suggests that calculation of energy from cutting force is a novelty – which is not a new concept. Please provide information about novelty of your work;

literature review should be improved providing more references to recent works from the area of described study,

it is surprised for me that authors did not recognize differences between velocity and volume – capital V is not a symbol of velocity!

according to ISO standard symbol of material removal (volume of workpiece material removed) is V_w in mm^3;

symbols used in the text should be corrected according to international standars;

at the end of the introduction should be clearly and concise given the research gap to create the appropriate lead up for the motivation of the work;

the novelty of given approach should be emphasized in introduction;

please provide more detailed information about machined material;

the Authors should more carefully and more detailed describe methodology of experiments;

I suggest to provide more precise information about used experimental and measurement positions;

2 should provide information abut vectors of movements;

in the discussion section should be provide more references to already known results from literature;

the strengths and limitations of the obtained results and applie
methods should be clearly described;

I suggest to provide the main conclusions as numbered sentences and refer to specific values (results of analysis) as well as basic phenomena that cause described results.

After a careful study of the text sent for review, many editorial comments also come to mind:

quality of figure 1 is not appropriate for publication;

all mathematical/physical symbols should be write italics and proper subscript/superscript notation for better readability of the text (also on figures);

synthetic list of main nomenclature (symbols and acronyms) would improved readability of this study,

lack of punctuation marks after equitation (equitation is part of a sentence).

Submission Date	18 January 2021
Date of this review	21 Jan 2021 13:20:12

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Journal	Metals (https://www.mdpi.com/journal/metals) (ISSN 2075-4701)
Manuscript ID	metals-1097568
Type	Article
Number of Pages	11
Title	Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors	Rusdi Nur , M. Y. Noordin * , S. Izman , Fethma M Nor , Denni Kurniawan *
Abstract	Downsizing energy consumption during machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. In this paper, we propose using measured cutting force to calculate power consumption during the turning process of metals. A case study was carried out where hardened stainless steel was turned using coated carbide tool without cutting fluid. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm/rev) while other parameters were kept constant. The results indicate that energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data. This generally means cutting force can be used to calculate energy consumption during the turning of metals, provided sufficient data is available. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

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Authors' Responses to Reviewer's Comments (Reviewer 2)

Author's Notes	Thank you for the comments. We compiled the response in attached file.
Author's Notes File	Report Notes (/user/review/displayFile/16134126/C0zJqBEc?file=author-coverletter&report=10469508)

Review Report Form

English	( ) Extensive editing of English language and style required

language and style

( ) Moderate English changes required
(x) English language and style are fine/minor spell check required
( ) I don't feel qualified to judge about the English language and style

	Yes	Can be improved	Must be improved	Not applicable
Does the introduction provide sufficient background and include all relevant references?	(x)	( )	( )	( )
Is the research design appropriate?	(x)	( )	( )	( )
Are the methods adequately described?	(x)	( )	( )	( )
Are the results clearly presented?	( )	(x)	( )	( )
Are the conclusions supported by the results?	(x)	( )	( )	( )

Comments and Suggestions for Authors

The authors investigated energy consumption during turning process based on measured cutting force. The manuscript is recommended to publish after the following comments are considered:

Lines 177-178: for simplicity reason, it may be convenient to omit the E5 contribution. However, the tool life could correlate strongly with the energy consumed in supplying workpiece material. A short tool life would require more tool materials in the same operational or cutting time. Please comment on this.

Line 199: please explain the terms used in Table 3, such as "DF", "Prob > F", etc., although a reference is given by [23].

Line 231: please add the units used for "Cutting force", "Feed rate" and "Cutting speed" in Fig. 4.

Line 279: please add the units used for "Cutting force" and "Feed rate" in Fig. 6.

Submission Date 18 January 2021

Date of this review 02 Feb 2021 01:09:25

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Journal	Metals (https://www.mdpi.com/journal/metals) (ISSN 2075-4701)
Manuscript ID	metals-1097568
Type	Article
Number of Pages	11
Title	Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
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Abstract	Downsizing energy consumption during machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. In this paper, we propose using measured cutting force to calculate power consumption during the turning process of metals. A case study was carried out where hardened stainless steel was turned using coated carbide tool without cutting fluid. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm/rev) while other parameters were kept constant. The results indicate that energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data. This generally means cutting force can be used to calculate energy consumption during the turning of metals, provided sufficient data is available. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

The coverletter for this review report has been saved in the database. You can safely close this window.

Authors' Responses to Reviewer's Comments (Reviewer 3)

Author's Notes	Thank you very much for the extensive comments. We compiled our response in attached file. Thank you.
Author's Notes File	Report Notes (/user/review/displayFile/16140954/WUGrE9Mu?file=author-coverletter&report=10475156)

Review Report Form

English	( ) Extensive editing of English language and style required

language and style	( ) Moderate English changes required ( ) English language and style are fine/minor spell check required (x) I don't feel qualified to judge about the English language and style

	Yes	Can be improved	Must be improved	Not applicable
Does the introduction provide sufficient background and include all relevant references?	( )	( )	(x)	( )
Is the research design appropriate?	( )	( )	(x)	( )
Are the methods adequately described?	( )	( )	(x)	( )
Are the results clearly presented?	( )	( )	(x)	( )
Are the conclusions supported by the results?	( )	( )	(x)	( )

Comments and Suggestions for Authors

Comment 1: The title of the article talks about energy consumption. We know potentially and kinetic energy from a physical point of view. This article does not use these terms. In technological practice, it is customary to calculate or measure the energy in machining through the machining power. For these reasons, it would be appropriate to reconsider the title of the article.

Comment 2: The issue of consumption energy itself, the article, which has a total of 11 pages, deals with only about 4 pages. I recommend giving more space to the issue of measuring the energy consumed respectively machining power or more precisely the cutting power.

Comment 3: In cutting theory, when turning, the unit (mm) is used for "feed".

Comment 4: Line 88 citation: "First is the cutting force or tangential force (*Fc*)", in machining theory the term "main" is used instead of "first".

Comment 5: Line 93 citation: „..., commonly only the cutting force is considered.“, it is correct: “… commonly only the tangential cutting force is considered.”.

Comment 6: Line 86 -90, I recommend inserting the text "of cutting force (*F*)" into: "There are three cutting force components of cutting force (*F*) in the turning process, ...".

Comment 7: Improve image quality Fig. 1. Incorrectly marked cutting force components. Incorrectly drawn cutting speed vector. Add a legend for symbols to the image.

Comment 8: For the cutting speed we use symbol $v_{c\,,}$ i.e. with a lowercase "*v*" and an index with a capital "*C*".

Comment 9: Inappropriate division of the text into subchapters, e.g. Chapter 2 is too short.

Comment 10: unify the writing of equations e.g. in many equations the multiplication sign is not given and for others it is given as "*".

Comment 11: The mathematical apparatus given in equations (1) - (10) is not demonstrably used in this article. This whole state can be replaced simply by the text: "It is known that we calculate the cutting power using the equation $Pc = Fc\ v_c$, where Pc is the cutting power, Fc is the main component of the cutting force and v_c is the main component of the cutting speed (often referred to as cutting speed). "

Comment 12: It would be appropriate to compare the energy calculation and energy measurement, the calculation using the measured cutting force and the measurement using the electrical power on the spindle during machining.

Comment 13: Line 99, The title of the chapter does not describe its content. I recommend specifying the title of the chapter.

Comment 14: Line 114, I quote: "... in a previous study that ...", it would be appropriate to insert a reference to said study here.

Comment 15: Line 114 -120, the division of energies is confusing, for the purposes of this article, the expression on line 151 - 154 is enough.

Comment 16: An unusual number of references to experimental results taken from other sources, then the question is, what did this article bring?

Comment 17: Line 146, which means "(MJ)", if it is the unit in megajoules, then it is too exaggerated, too large in machining, please adjust?

Comment 18: Equation (5), (6) in my opinion the product of power P_0 i. power idle with cutting time tc is illogical. So the next way of deriving equations is illogical and incorrect?

Comment 19 Line 234-235, reference to equation (9), which is not for calculating energy E_2?

Comment 20: It seems serious to me that data for energy calculation is missing. Would it be appropriate to summarize this data in tabular form? It is not possible to check the calculation of energy consumption, e.g. 417.11 kWs.

Comment 21: Line 168, this is an unfinished sentence.

Comment 22: The description of the experiment is insufficient, especially data on the cutting tool are missing - tool holder, cutting wedge geometry, turning strategy (as tool path), workpiece diameter, workpiece rotation frequency, workpiece blank dimensions, surface condition before machining (especially roughness), characteristics cutting material (substrate, grain size).

Comment 23: Justify the choice of cutting speeds (size and range) and the choice of feeds (size and range) for the experiment?

Comment 24: In chapter 5.4, I recommend adding: optimization mathematical model (system of inequalities), target function, selected extreme of the target function, calculate optimal cutting parameters in terms of minimum energy consumption (power). This is necessary due to the construction of the vc-f graph.

Comment 25: In the chart: vc-f, Figure 6,

- indicate the "optimal cutting parameters",

- explain what the red dots mean,

- optimization graph vc-f, for simplicity, we draw in logarithmic coordinates, i. log vc - log f,

- data for graph construction are missing.

Comment 26: Line 235-236, the assertion that maximum energy was found for lowest cutting speed and lowest feed can be considered a very unusual assertion from cutting theory. I assume that the experiment or calculations were performed incorrectly. ***In this case, a very precise justification is needed, for example in the form of the Discussion chapter***. I mean, in classical cutting theory, we have the following:

1. If the feed *f* increases, then the cutting force *Fc* increases, and then the equation $Pc = Fc\ v_c$ shows that the cutting power *Pc* also increases. If the cutting power increases, then according to the equation $E_2 = Pc\ tc$ it follows that the consumed energy E_2 also increases!
2. If the cutting speed v_c increases, then the equation $Pc = Fc\ v_c$ shows that the cutting power *Pc* also increases. If the cutting power increases, then according to the equation $E_2 = Pc\ tc$ it follows that the consumed energy E_2 also increases!

But the findings of the authors are of the opposite nature, i. that at a higher cutting speed v_c and a higher feedrate *f* a lower energy consumption E_2 was found?

Comment 27: In the Conclusion chapter, I recommend emphasizing the results achieved both qualitatively and quantitatively and commenting briefly on all the results achieved.

Submission

Submission Date	18 January 2021
Date of this review	27 Jan 2021 16:28:40

[Metals] Manuscript ID: metals-1097568 - waiting for your resubmission

1 pesan

Metals Editorial Office <metals@mdpi.com> 15 Februari 2021 15.49
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Dear Dr. Kurniawan,

We sent a revision request for the following manuscript on 28 January 2021.

Manuscript ID: metals-1097568
Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force

May we kindly ask you to update us on the progress of your revisions? If you have finished your revisions, please upload the revised version together with your responses to the reviewers at this link:
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Kind regards,
Lina Fan, M.Sc.
Section Managing Editor
Email: lina.fan@mdpi.com

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Politeknik Negeri
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[Metals] Manuscript ID: metals-1097568 - Revision Reminder

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Dear Dr. Kurniawan,

We sent a revision request for the following manuscript on 28 January 2021.

Manuscript ID: metals-1097568
Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors: Rusdi Nur, M. Y. Noordin *, S. Izman, Fethma M Nor, Denni Kurniawan *
Received: 18 January 2021
E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn

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Aaron Han, M.Sc.
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Rusdi Nur <rusdinur@poliupg.ac.id>

[Metals] Manuscript ID: metals-1097568 - May we expect to receive your revision on Monday?

10 pesan

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Cc: "aaron.han@mdpi.com" <aaron.han@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Dr. Kurniawan,

We invited you to revise your paper last week. As we have not received your revised manuscript yet, we would like to know the status of your revision. May we expect to receive your revision on Monday (2 February 2021)? Please let us know if you need more time.

Look forward to hearing from you soon.

Kind regards,
Sunny He
Managing Editor

On 2021/2/4 9:31, aaron.han@mdpi.com wrote:

> Dear Dr. Kurniawan,
>
> We sent a revision request for the following manuscript on 28 January 2021.
>
> Manuscript ID: metals-1097568 Type of manuscript: Article Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
>
> May we kindly ask you to update us on the progress of your revisions? If you have finished your revisions, please upload the revised version together with your responses to the reviewers as soon as possible.
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> Thank you in advance for your kind cooperation and we look forward to hearing from you soon.
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>
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>> Dear Dr. Kurniawan,
>>
>> Thank you for submitting the following manuscript to Metals:

Manuscript ID: metals-1097568 Type of manuscript: Article Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force Authors: Rusdi Nur, M. Y. Noordin *, S. Izman, Fethma M Nor, Denni Kurniawan * Received: 18 January 2021 E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn

It has been reviewed by experts in the field and we request that you make major revisions before it is processed further. Please find your manuscript and the review reports at the following link:

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Please revise the manuscript according to the reviewers' comments and upload the revised file within 5 days. Use the version of your manuscript found at the above link for your revisions, as the editorial office may have made formatting changes to your original submission. Any revisions should be clearly highlighted, for example using the "Track Changes" function in Microsoft Word, so that changes are easily visible to the editors and reviewers. Please provide a cover letter to explain point-by-point the details of the revisions in the manuscript and your responses to the reviewers' comments. Please include in your rebuttal if you found it impossible to address certain comments. The revised version will be inspected by the editors and reviewers. Please detail the revisions that have been made, citing the line number and exact change, so that the editor can check the changes expeditiously. Simple statements like ‘done’ or ‘revised as requested’ will not be accepted unless the change is simply a typographical error.

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Do not hesitate to contact us if you have any questions regarding the revision of your manuscript or if you need more time. We look forward to hearing from you soon.

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Editorial Office E-mail: metals@mdpi.com http://www.mdpi.com/journal/metals/ -------------

> > anyone.

Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 8 Februari 2021 19.13
Kepada: "metals@mdpi.com" <metals@mdpi.com>
Cc: "aaron.han@mdpi.com" <aaron.han@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Ms He and Mr Han,

Thank you for the reminder.
We are still working on the revision and response to Reviewers' comments. Considering currently the semester is active and other asap tasks, we have to inevitably delay in submitting the revision. Please allow us until next week Wednesday (17 February 2021) for the resubmission. Really appreciate your kind consideration. Thank you.

Best wishes,
Denni
[Kutipan teks disembunyikan]

____

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aaron.han@mdpi.com <aaron.han@mdpi.com> 22 Februari 2021 10.03
Kepada: "Dr. Denni Kurniawan" <denni.kurniawan@utb.edu.bn>
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Dear Dr. Kurniawan,

As we have not received your revised manuscript yet, we would like to know the status of your revision. Please let us know if you need more time.

Look forward to hearing from you soon.

Kind regards,
Mr. Aaron Han
Assistant Editor

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[Kutipan teks disembunyikan]

Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 22 Februari 2021 10.19
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Dear Mr Han,

Thank you for the reminder. Yes indeed we need more time to complete the revision. We need another weekend, so I would like to notify that we will submit the revision by 1 February 2021. Pardon again for the delay.
Best wishes,
Denni

From: aaron.han@mdpi.com <aaron.han@mdpi.com>
Sent: 22 February 2021 10:03 AM
To: Dr. Denni Kurniawan
Cc: metals@mdpi.com; Rusdi Nur; M. Y. Noordin; S. Izman; Fethma M Nor
Subject: Re: [Metals] Manuscript ID: metals-1097568 - May we expect to receive your revision on Monday?
[Kutipan teks disembunyikan]

Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 22 Februari 2021 10.48
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Cc: "metals@mdpi.com" <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Pardon, I meant 1 March 2021. As we also wish to publish the article as soon as possible, we intend not to request any further extension.

From: Dr. Denni Kurniawan
Sent: 22 February 2021 10:19 AM
To: aaron.han@mdpi.com
[Kutipan teks disembunyikan]

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aaron.han@mdpi.com <aaron.han@mdpi.com> 2 Maret 2021 09.54
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Dear Dr. Kurniawan,

We haven't received your resubmission. Could you please let me know the status of your revision? If you have finished, may I expect to receive your report Today? Or if you need more time to revise, please feel free to let us know.

You can upload your manuscript and coverletters at this link:
https://susy.mdpi.com/user/manuscripts/resubmit/9510c9a5400e15da5467995875d9dbab

We look forward hearing from you soon.

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[Kutipan teks disembunyikan]

Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 4 Maret 2021 16.03
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Cc: "metals@mdpi.com" <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Mr Han,

Thank you for the reminder. I am afraid I need to kindly ask for another week extension for finalising our revision and responses. Please allow us until 12 March 2021 for submitting the revision. Thank you.

Best wishes,
Denni

From: aaron.han@mdpi.com <aaron.han@mdpi.com>
Sent: 02 March 2021 9:54 AM
[Kutipan teks disembunyikan]

---

aaron.han@mdpi.com <aaron.han@mdpi.com> 15 Maret 2021 11.12
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Dear Dr. Kurniawan,

We haven't received your resubmission. Is everything going well? We quite understand your situation of meeting the deadline for improving the manuscript. Please let us know the status of manuscript revision and when can we receive it. If you have finished, please upload your manuscript and coverletters at this link:

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We look forward hearing from you soon.

Kind regards,
Mr. Aaron Han
Assistant Editor

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aaron.han@mdpi.com <aaron.han@mdpi.com> 18 Maret 2021 10.24
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Dear Dr. Kurniawan,

Hope this emails finds you well. We quite understand your situation of meeting the deadline for improving the manuscript. Please let us know if we can receive the revised manuscript within this week?

If you need more time to revise, would you mind withdraw and resubmit
the manuscript?   Then you can have enough time to revise. We will also
invite the same reviewers to review the resubmitted manuscript.

We look forward to your reply.

Kind regards,
Mr. Aaron Han
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Cc: "metals@mdpi.com" <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Mr Han,

Thank you for the reminder.
We also appreciate the option provided. Our revision is at final stage. We expect to submit it by Sunday. However, if we are not able to submit it by this weekend, then I will withdraw and resubmit it on Monday, as suggested. Thank you.
Best wishes,
Denni

____
From: aaron.han@mdpi.com <aaron.han@mdpi.com>
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Dear Dr. Kurniawan,

Thank you very much for resubmitting the modified version of the following manuscript:

Manuscript ID: metals-1097568
Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors: Rusdi Nur, M. Y. Noordin *, S. Izman, Fethma M Nor, Denni Kurniawan *
Received: 18 January 2021
E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn

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A member of the editorial office will be in touch with you soon regarding progress of the manuscript.

Kind regards,

MDPI

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Article

Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force

Rusdi Nur [1], Noordin Mohd Yusof [2,*], Izman Sudin [2], Fethma M. Nor [3] and Denni Kurniawan [4,*]

[1] Department of Mechanical Engineering, Politeknik Negeri Ujung Pandang, Makassar 90245, Indonesia; rusdinur@poliupg.ac.id
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* Correspondence: noordin@utm.my (N.M.Y.); denni.kurniawan@utb.edu.bn (D.K.)

Abstract: Downsizing energy consumption during the machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. The manufacturing process of interest is the finish turning which has been explored to generate (near) net shapes, particularly for hardened steels. In this paper, we propose using measured cutting forces to calculate the electrical energy consumption during the finish turning process of metals where typically the depth of cut is lower than the cutting tool nose radius. In this approach, the resultant cutting force should be used for calculating the energy consumption, instead of only the main (tangential) cutting force as used in the conventional approach. A case study was carried out where a hardened stainless steel (AISI 420, hardness of 47–48 HRC) was turned using a coated carbide tool, with a nose radius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm) while other parameters were kept constant. The results indicate that the electrical energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data as proposed. This generally means machining studies that measure cutting forces can also present energy consumption during the finish or hard turning of metals, without specifically measuring the power consumption of the machining process. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

Keywords: turning; cutting force; energy consumption; stainless steel

check for updates

Citation: Nur, R.; Yusof, N.M.; Sudin, I.; Nor, F.M.; Kurniawan, D. Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force. *Metals* **2021**, *11*, 565. https://doi.org/10.3390/met11040565

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Received: 18 January 2021
Accepted: 25 March 2021
Published: 31 March 2021

1. Introduction

With sustainable manufacturing in mind, a product's manufacture should minimize energy consumption and negative environmental impact [1]. From the sustainable manufacturing point of view, machining is a material removal process using machine tools, where it is wasteful in its use of both material and energy [2]. Yet, given that machining can produce shapes, sizes, and surface finishes with simplicity and accuracy, it is still the most widely used manufacturing process [1,3].

Researchers have introduced models to assess the environmental impact and energy consumption of machining. Munoz et al. [4] developed modeling approaches specifically to the environmental issues of machining processes. Later on, they presented a methodology for considering environmental factors in machining facilities which used analytical process models embedded as the attributes of systems resources to determine energy use and mass flow based on process time and volume of material removed. Choi et al. [5]

developed the assessment methodology to measure the amount of the generated solid waste, the consumed energy, the incurred wastewater, and the noise level for machining processes. For energy consumption, the analytical models proposed in previous works differentiate the machine tool's energy consumption between constant and variable energy consumptions. An empirical approach was presented by Kara and Li [6] in building models for machining processes in predicting their consumed energy for each unit process. They showed that the machining process's energy consumption could be predicted using the empirical models within the set cutting parameters for the selected machine tools. Their model can calculate the energy requirement for turning or milling processes to machine a product. An on-line approach proposed by Hu et al. [7] was developed based on an energy consumption model of a machine tool for energy efficiency monitoring. Another model was proposed by He et al. [8], seeing machining in a manufacturing system, by categorizing the machine tool's energy consumption based on the task. They found that the task flow's flexibility and variability influence the machining's energy consumption in a particular manufacturing system. These models were developed to reduce environmental impact and energy consumption when machining metals.

Reducing energy consumption requires the capability of monitoring the machining process's energy consumption [9]. To better calculate the energy consumption, we need to incorporate the machining conditions into energy consumption. However, this is challenging considering the complexity of manufacturing systems and a large amount of data. Previous studies on this include automated monitoring and analysis of energy consumption in manufacturing systems using event stream processing techniques [10]. Another work by Rajemi et al. [11] includes optimization of the energy footprint of a machined product in developing the energy consumption model. As a case study, they machined a part by turning and analyzed the total consumed energy of the process. Afterward, the minimum energy footprint was determined during the optimization of the total energy consumption concerning the machine tool's tool life.

The turning process of hardened steels is gaining ground with empirical evidence that it can be done, to a certain extent, as a finishing process to get net shapes or near-net shapes of cylindrical or conical parts [12]. As a finishing process, hard turning is typically done at a low depth of cut, lower than the nose radius of the cutting tool. We identified that many works on hard turning reported the effect of machining parameters (e.g., cutting speed, depth of cut, and feed) to quantitative machining responses like cutting forces, tool life, surface roughness, and cutting temperatures. There is only a limited number of studies that are addressing the electrical energy consumption as a machining response in turning of steels, even more for hard turning. Among the few are the works of Astakhov and Xiao [13] and Li and Kara [14] in the turning of steels. These works calculated the machining energy through the measured electrical power consumption and the machining time. These works also acknowledge that power consumption can also be obtained from the multiplication of the main cutting force (i.e., tangential cutting force) and the cutting speed. The only work related to hard turning is by Chudy et al. [15] which also indirectly measured the energy as the product of the tangential cutting force, the cutting speed, and cutting time.

The simplification in calculating the machining power consumption through the use of the main cutting force only is derived from an established theory, with the assumption that the main force contributes the most to the resultant cutting force. However, we observed that the other force components other than the main cutting force are not negligible in finish hard turning. This is also true for the work on hard turning above [15], where the cutting force in the radial direction was higher than the main cutting force for some cutting parameters.

Based on these observations, in this study, we propose the use of resultant cutting force to approximate the electrical energy consumption in the hard turning of steels. As a case study, hardened stainless steel was turned under varying cutting speed and feed conditions, using a carbide tool without cutting fluid. We calculated the energy consumption and further determined the optimum machining parameters region based on the machining responses specified, which also include machining energy.

2. Cutting Forces and Energy Consumption Calculation in Finish Turning Process

The information on cutting forces during various machining processes is essential for determining machinability. Some uses of measuring cutting forces during the machining process include machining economics analysis, adaptive control applications, and numerical modeling of the machining process. As machining responses, cutting forces are studied in various machining processes. Models of cutting forces are formulated to correlate between the machining parameters to cutting forces. The empirical models are based on the established machining theory.

There are three cutting force components of the cutting force (F) in a turning process, which are designated according to the direction of the cutting tool's relative movement to the workpiece (Figure 1). The cutting force components are tangential force (F_c) in the direction of the main cutting action, radial force (F_r) in the direction toward the axis of the workpiece, and feed force (F_f) in a parallel direction to the workpiece axis [16,17].

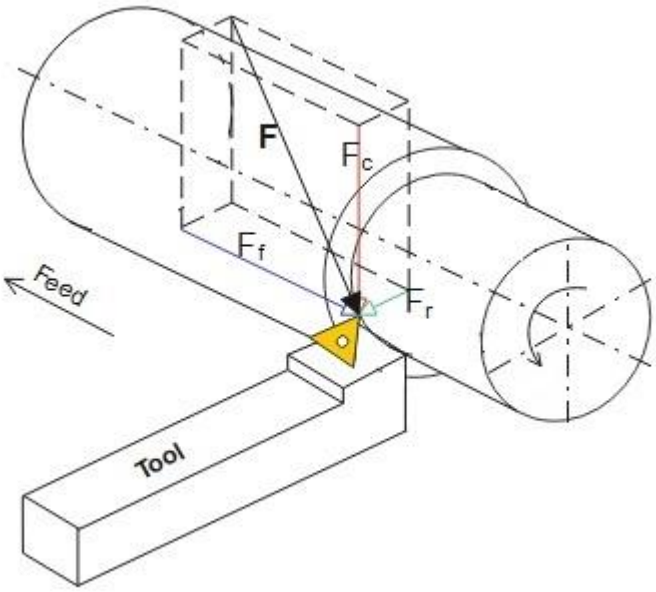

Figure 1. Cutting force components in the turning process, where F is resultant cutting force, F_c tangential force, F_r radial force, and F_f feed force.

During the turning process, power consumption can be an indicator of tool conditions and as a design criterion of the machining input. To determine the power consumption, which is calculated as the product of the cutting force and the cutting speed, only the tangential cutting force is considered for the former. This simplification was rooted in the use of orthogonal cutting theory in the relationship between machining power and cutting force. It is a common practice that tangential cutting force is used to represent the cutting force considering it makes the majority among the three force components [13,18,19].

However, we observed that for finish turning processes of steels, where the depth of cut is low—at times even lower than the nose radius of the cutting tool—the radial and feed forces are not negligible [16–18]. The feed force is indeed the lowest among the three, but its value is not that small. In some works, the radial force is even higher than the tangential cutting force for some cutting parameters [15,18]. Hence, in this study, the cutting force (F) which is the resultant of all three force components is used. It can be calculated by Equation (1),

$$P_c = v_c \cdot F \tag{1}$$

where P_c is the power consumption (W), v_c is the cutting speed (m/min), and F is the resultant cutting force (Newton).

Studies on determining the machining process's energy consumption commonly differentiate the electrical energy consumption in the idle, run-time, and production modes [10,11]. Idle mode is when the machine is ready for or in between machining. Although no material removal action is performed, there is still constant energy consumption in standby mode (for example, for the operation panel and fans). Run-time mode is when the auxiliaries are on (e.g., motor for the spindle and pump for the cutting fluid) but there is no material removal action. This consumes constant energy. Production mode is when the material removal action occurs. It varies and depends on the applied load towards the machine.

Factors that affect energy consumption include cutting parameters, cutting tools, and workpiece material [16–20]. Studies found that compared to the total energy consumption, the energy consumption during production mode where material removal action occurs is small [21,22] Considering this, efforts to lower energy consumption are focused more on reducing the constant energy. Some approaches include specific components improvement or overall cycle time reduction [5,23].

We agree with the approach proposed in a previous study [6] that the total energy consumption (E) for the turning process is a summation of the energy consumption during setup (E_1), when performing material removal (E_2), for tool change (E_3), to fabricate the cutting tool (with all its cutting edges) (E_4) and in the manufacture of the workpiece material (E_5). Considering that the workpiece material is given depending on the product and the machine shop has limited control over the energy contained in the particular workpiece material, this factor can be omitted during the machining process itself.

From the above, for the turning process, the total energy can be calculated as Equation (2),

$$E = E_1 + E_2 + E_3 + E_4 \tag{2}$$

where E_1 is the energy used during machine setup. It can be calculated as a product of the setup time and the corresponding power consumption, as shown in Equation (3),

$$E_1 = P_0 \cdot t_1 \tag{3}$$

where P_0 is the power (W) in idle and run-time modes and t_1 is the time (s) required for machine setup.

E_2 is the machining energy consumption. It is calculated by multiplying the actual machining time by the corresponding power consumption (Equation (4)) [21],

$$E_2 = \left(P_0 + k \cdot \dot{v}\right) \cdot t_2 \tag{4}$$

where k is specific machining energy (Ws/mm^3), $\dot{v}$ is material removal rate (mm^3/s) and t_2 is the accumulated material removal time of the turning process (s). In this context, t_2 can also be identified as tool life T. The value for specific machining energy k can refer to [24]. Considering Equation (1), the calculation for E_2 can also be done by using P_c which is the power of the machine tool, and acknowledging that t_2 is t_c which is the actual cutting time, making Equation (5),

$$E_2 = (P_\text{o} + P_\text{c}) \cdot t_\text{c}. \tag{5}$$

Thus, the Equation for machining energy consumption becomes Equation (6),

$$E_2 = (P_\text{o} + F \cdot v_\text{c}) \cdot t_2. \tag{6}$$

E_3 is the energy used during the replacement of a tool and is calculated as a product of the time required for tool changes and the associated power. In the turning process, tool replacement is conducted manually or using an automated tool changer, both of which occur when the tool is retracted away from the workpiece. Thus, it can be assumed that the energy used during the replacement of the tool is as much as the power when the machine is in a no-load position, which is Equation (7).

$$E_3 = P_0 \cdot t_3 \cdot \left(\frac{t_2}{T}\right) \tag{7}$$

where t_3 is the time for a replacement tool (s) and T is tool life (s), which is the same with t_2 and hence making the notation in the bracket a unity.

E_4 can be calculated as the sum of energy consumed to fabricate each cutting edge (y_E) on a cutting tool. Note that cutting tools in the form of indexable inserts usually have multiple cutting edges. So, this energy should be divided by the number of edges needed to perform the turning process (Equation (8)),

$$E_4 = y_E \cdot \left(\frac{t_2}{T}\right) \tag{8}$$

where y_E can be obtained from the total energy per insert (MJ) for material and manufacturing process and that refer to [24].

Based on the description above, the Equation to calculate the energy consumed in a turning process can be written as Equation (9),

$$E = P_0 \cdot t_1 + (P_o + F_c \cdot v_c) \cdot t_2 + P_0 \cdot t_3 + y_E \tag{9}$$

or as Equation (10),

$$E = P_0 \cdot t_1 + \left(P_0 + k \cdot \dot{v}\right) t_2 + P_0 \cdot t_3 + y_E. \tag{10}$$

Based on both Equations (9) and (10), the total energy consumption is only distinguished in the calculation of energy during the actual cutting process (E_2), which is categorized as the variable factor. Other factors, i.e., E_1, E_3, and E_4 are the same for both Equations (9) and (10) and are considered as constant factors in energy consumption calculation [6].

3. Case Study

3.1. Experimental

As a case study, a previous experiment [25] is referred to. Briefly, it is a hard turning process of stainless steel using a coated carbide tool in a two-axis CNC lathe machine rated at 5.5 kW with a varied cutting speed of 100, 130, and 170 m/min, with a varied feed of 0.1, 0.125, and 0.16 mm, and with a constant depth of cut of 0.4 mm. In determining the lower and upper values of the cutting parameters, the recommendation by the cutting tool manufacturer for finish turning a stainless steel workpiece with a hardness of up to 48 HRC was considered (ASSAB Steel, Shah Alam, Malaysia). As the depth of cut was 0.4 mm, the selected lower and upper limit values for cutting speed were 100 and 170 m/min, respectively, and for feed were 0.1 and 0.16 mm, respectively. The middle values were 130 m/min for cutting speed and 0.125 mm for feed. The turning process was performed dry (without any cutting fluid). The workpiece material was an AISI 420 martensitic stainless steel, with a chemical composition of 0.38% C, 13.6% Cr, 0.3% V, 0.9% Si, 0.5% Mn, and balance Fe (ASSAB Steel, Shah Alam, Malaysia). The stainless steel was expected to have corrosion resistance, stability at a hardened state, and to result in a fine surface finish for plastic mold applications. The stainless steel was hardened throughout by heat treatment to reach a hardness value of 47–48 HRC. Before the machining trial, the workpiece surface was finish turned using the last set of cutting parameters. The cutting tool used for the experiment was a TiAlN coated carbide tool (Kennametal, Shah Alam, Malaysia) that is designated as CNMG 120408. The cutting tool was a fine-grained WC-6% Co substrate coated with 3.0 to 35 m thick TiAlN through physical vapor deposition. The cutting tool was mounted on a holder with an ISO designation of MCLNL 1616-H12, giving the 10° rake angle, −5° side cutting edge angle, and 5° relief angle. The positive rake angle—commonly hard turning sets negative rake angle—was due to the tool has a 15° chip breaker profile, despite the tool holder actually positions the cutting tool at $-5°$ angle. The tool wear was measured according to ANSI/ASME B94.55M-1985 standard, subjected to the maximum flank wear width (V_{Bmax}) within the nose radius of the tool (zone C). An optical microscope (Stemi 200-C, Carl Zeiss, Petaling Jaya, Malaysia) with an image analyzer was used for this purpose. Surface roughness (*Ra*) was measured by a surface profilometer (Accretech Handysurf, Tokyo Seimitsu, Tokyo, Japan) at 0.8 mm cut off length and 4 mm sampling length in each measurement. The tool life criteria were at a maximum of 0.14 mm of flank wear width, at the machined surface roughness Ra beyond 1.6 μm, or severely damaged cutting tool.

The experiments measured the cutting force elements in all three directions (F_c, F_r, and F_f is the schematic layout below (Figure 2). A three-component turning dynamometer (Kistler, Type 9265B, Singapore) with data acquisition software was used for this purpose. For measuring the electrical power consumption of the turning process, three portable power monitors (Omron ZN-CTX21, Johor Bahru, Malaysia) with three clamp meters (Omron ZNCTM11, Johor Bahru, Malaysia) were used. One power monitor was used to measure the main power while the other two to the spindle and axis drives. The measured power data was acquired and visualized using Wave Inspire ES (Omron, Johor Bahru, Malaysia) software.

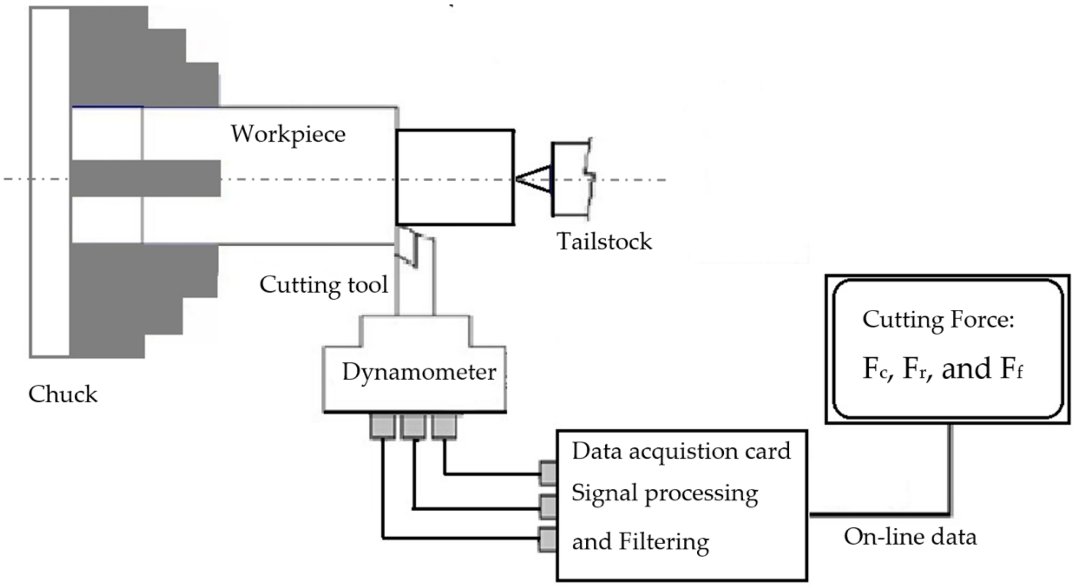

Figure 2. Schematic layout of cutting force measurement setup.

3.2. Experimental Design

Response Surface Methodology (RSM) was chosen for the design of experiments. A commercial software (Design Expert, StatEase, Minneapolis, MN, USA) was used for this purpose. For the RSM, regression is used to approximate the machining response based on the relationship between one or more factors (input variable) and the estimated response, y_{est}. The fitting of the model Equation was using the least square technique through residual error minimization. The model Equation and its coefficients were tested for statistical significance. Analysis of variance (ANOVA) was used for this purpose. For the case at hand, a three-level factorial design having two input factors and 2 center points was applied, making 11 runs in total (Table 1). The type 1 error (α) value was set at 0.05 for the models and its coefficients to be considered significant.

Table 1. Factor and levels for the experiments.

Factor	Coded Form		
	−1	0	1
x_1–cutting speed (m/min)	100	130	170
x_2–feed (mm)	0.10	0.125	0.16

4. Results and Discussion

4.1. Surface Roughness and Tool Life

The experimental results for surface roughness and tool life for all eleven trials are summarized in Table 2 [25].

Table 2. Experimental results for surface roughness and tool life. (Note: v_c is cutting speed, f feed, Ra surface roughness, and T tool life).

v_c (m/min)	f (mm)	Ra (µm)	T (min)
100	0.10	0.60	30.50
130	0.10	0.54	8.84
170	0.10	0.47	3.93
100	0.125	0.87	19.20
130	0.125	0.73	5.50
170	0.125	0.50	3.90
100	0.16	0.92	15.00
130	0.16	0.78	4.65
170	0.16	0.74	2.50
130	0.125	0.42	5.18
130	0.125	0.68	7.00

Based on the results of surface roughness and tool life, a selection of models using regression calculations were made [26]. The linear model was chosen for modeling the surface roughness while the quadratic model was most suitable for the tool life. The backward elimination procedure was selected to automatically reduce the terms that are not significant and the resulting ANOVA table for the reduced linear model for surface roughness and the reduced quadratic model for tool life is displayed in Table 3 [25]. The ANOVA table shows the statistics used to test the hypotheses about the population means.

Table 3. Result of ANOVA table for tool life and surface roughness.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Value	p Value
Surface roughness					
Model	0.19	2	0.095	8.94	0.009
x_1	0.07	1	0.07	6.8	0.031
x_2	0.12	1	0.12	11.13	0.01
Residual	0.09	8	0.01		
Cor Total	0.28	10			
Tool Life					
Model	5.73	3	1.91	104	<0.001
x_1	4.92	1	4.92	267.93	<0.001
x_2	0.53	1	0.53	28.99	0.001
x_1^2	0.57	1	0.57	31.27	0.008
Residual	0.13	7	0.018		
Cor Total	5.86	10			

In an analysis of variance, the total variation in the response measurements, in this case, the surface roughness and tool life values, are partitioned into variation which can be explained by the independent variables or factor effects (Model) and the variation which is not explained by the independent variables (Residual which is also called Error). In the case of surface roughness, the model is made up of the main effects of cutting speed, x_1, and feed, x_2. Thus, the Sum of Squares for the independent variables, x_1 and x_2, add up to become the Sum of Squares for Model. Whilst the Sum of Squares for Model and Residual add up to the Total Variance.

Degrees of freedom are associated with the sources of variance. The total variance has N-1 degrees of freedom, where N is the total number of experiments. In this case, there were N = 11 experiments, so the degrees of freedom for total is 10. The degrees of freedom for the model is the sum degrees of freedom of the independent variables or factor effects which explains the variation. In the case of independent variables or factor effects, the degrees of freedom for each independent variable or factor effect is the number of levels -1. Thus, for cutting speed, the degrees of freedom is $2 - 1 = 1$ and this is similar to the degrees of freedom for feed. The degrees of freedom for the model is therefore $1 + 1 = 2$. The degrees of freedom residual is the degrees of freedom total minus the degrees of freedom model, which is $10 - 2 = 8$. The respective Mean squares are computed by dividing the respective Sum of squares by their respective degrees of freedom. The respective F ratios are computed by dividing the respective Mean squares by the Mean square residual or error and these are used to test the significance of the predictors in the model. The p-value associated with these F values are small, 0.031 or less. The p value is compared to the alpha level (typically 0.05) and, if it is smaller, then the independent variable or factor effects is statistically significant. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted thus indicating differences in the mean values of the respective independent variables or factor effects.

The final equation, in terms of actual factors, acquired from the model for surface roughness is as in Equation (11),

$$Ra = 0.4793 - 0.0031 \cdot v_c + 4.6513 \cdot f \tag{11}$$

where Ra is surface roughness (μm), v_c *is* cutting speed (m/min), and f is feed (mm/rev).

For tool life, the logarithmic transformation is recommended based on the best lambda value found at the minimum point of the Box–Cox curve generated by the natural log of the sum of squares of the residuals. The final equation, in terms of actual factors, achieved from the model for tool life can be expressed as in Equation (12),

$$Ln\ T = 13.4177 - 0.1297 \cdot v_c - 9.8739 \cdot f + 0.0004 \cdot {v_c}^2 \tag{12}$$

where T is tool life (min) and the other variables were as defined previously.

4.2. Cutting Force

The experimental results for cutting force and the respective calculated machining energy for all trials are summarized in Table 4. The machining time t_2 is the tool life in second. F is the resultant cutting force calculated from the measured tangential force F_c, radial force F_r, and feed force F_f. The trend in cutting force values where the feed force is the lowest among the three force components and where the radial force is higher than the tangential force at some cutting parameters is in agreement with previous work on the hard turning of AISI 5140 (55 ± 1 HRC hardness) using CBN (cubic boron nitride) tool at 150–300 m/min cutting speed, 0.05–0.2 mm feed, and 0.2 mm depth of cut [15].

Table 4. Experimental results for cutting force and machining energy. (Note: v_c is cutting speed, f feed, t_2 tool life (in second), F_c tangential force, F_r radial force, F_f feed force, F resultant cutting force, E_2 calculated machining energy based on Equation (6), and $E_2{}^{\#}$ calculated machining energy based on Equation (4)).

v_c (m/min)	f (mm)	t_2 (s)	F_r (N)	F_c (N)	F_f (N)	F (N)	E_2 (kWs)	$E_2{}^{\#}$ (kWs)
100	0.10	1830	103	80	39	136.12	417.11	428.93
130	0.10	530.4	100	75	38	130.65	152.07	162.81
170	0.10	235.8	96	73	35	125.58	85.82	95.46
100	0.125	1152	128	110	44	174.41	336.80	337.93
130	0.125	330	125	115	42	174.97	127.03	127.05
170	0.125	234	123	100	41	163.74	110.48	117.95
100	0.16	900	127	124	45	183.11	276.59	337.93
130	0.16	279	118	120	43	173.70	106.93	137.33
170	0.16	150	114	118	41	169.12	73.80	97.13
130	0.125	310.8	120	106	40	165.03	111.13	119.77
130	0.125	420	124	113	43	173.19	112.84	161.18

The model selection and its subsequent reduction as well as the empirical Equation development for cutting force were performed in the same manner as those for surface roughness and tool life [25]. The resulting ANOVA is as shown in Table 5.

Table 5. Result of ANOVA for cutting force F.

Source	Sum of Square	Degrees of Freedom	Mean Square	F Value	p Value
Model	3988.78	3	1329.59	134.33	<0.001
x_1	205.99	1	205.99	20.81	0.003
x_2	594.82	1	594.82	60.10	<0.001
$x_2{}^2$	1154.27	1	1154.27	116.62	<0.001
Residual	69.29	7	9.90		
Cor Total	4058.06	10			

The final Equation obtained from the model for cutting force can be expressed in terms of actual factors as in Equation (13),

$$F = -299.88 - 0.17{\cdot}v_c + 6895.59{\cdot}f - 23667.19{\cdot}f^2 \tag{13}$$

where F is the resultant cutting force (N).

The final model Equation for cutting force can be shown as a 3D contour graph (Figure 3). From Equation (13) and Figure 3, it can be observed that the cutting force is affected significantly first by the feed and second by the cutting speed. Generally, the feed is proportional to the cutting force while the cutting speed is inversely proportional to the cutting force. The proportionality relation between feed and cutting force is as expected since feed increase means the higher surface area of the workpiece to machine by the cutting tool [25]. The finding on cutting speed effect to cutting force was analyzed to be due to the higher cutting temperature at high cutting speed softened the workpiece and there was a transition from low to high cutting speed indicated by the change in chip type from continuous to segmented [25].

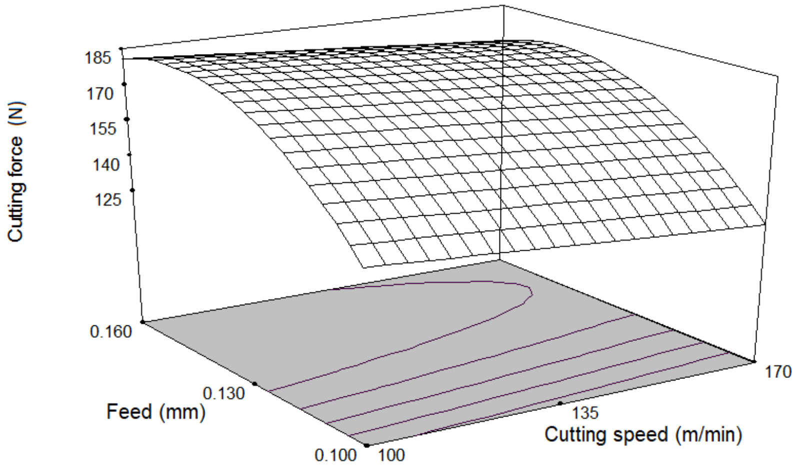

Figure 3. Response surface graph of 3D surface for *F*.

4.3. Energy Consumption

The maximum energy for the turning process (E_2) was calculated using cutting force data, as in Equation (6). The power consumption in idle and run-time modes P_0 was measured to be 1925 W. The maximum energy for the turning process, E_2, of 417.11 kWs was shown by the lowest of cutting speed and feed, while the minimum energy for the machining process (73.8 kWs) for cutting speed and feed rate is high (Figure 4). We calculated that E_1, E_3, and E_4 were 3.85 kWs, 5.58 kWs, and 1325 kWs, respectively. Compared to the total machining energy, the actual machining energy E_2 is low (5–20% of total energy), in agreement with a previous study [21,22].

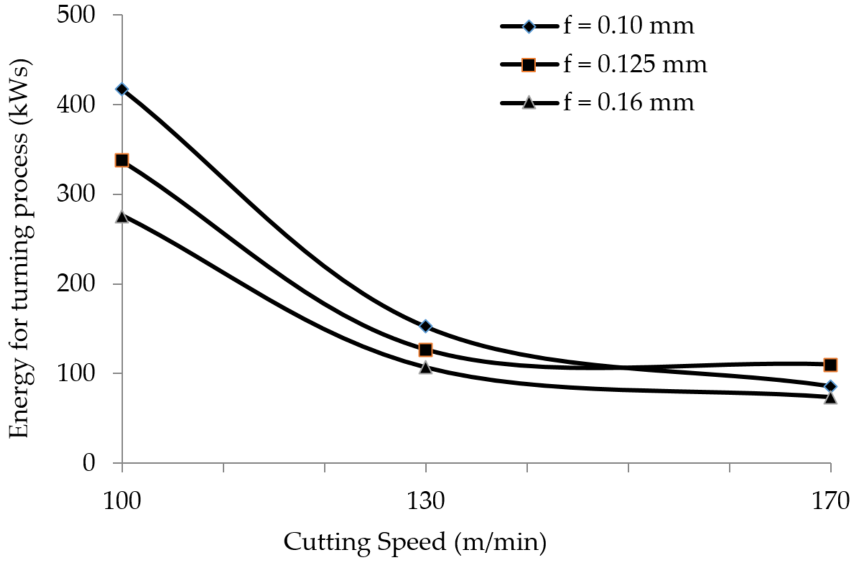

Figure 4. Energy for turning process (E_2) at various cutting speeds and feed.

For comparison, we also calculated E_2 using Equation (4), with specific machining energy k 3.5 Ws/mm^3 and material removal rate $\dot{v}$ (in mm^3/s) calculated by multiplying cutting speed, feed, and depth of cut. We found that the values are comparable with the machining energy E_2 calculated using resultant cutting force as proposed in this study. Had the tangential cutting force was used like in the conventional approach instead of resultant cutting force, the calculated machining energy E_2 will be 57–70% of the calculated values in this study.

The quadratic model was chosen to represent the data of E_2 because it has the least probabilistic value. ANOVA of the selected regression model and its coefficients was performed (Table 6).

Table 6. ANOVA for machining energy consumption (E_2).

Source	Sum of Square	Degrees of Freedom	Mean Square	F Value	p Value
Model	130,900.00	4	32,715.34	98.39	<0.001
x_1	93,449.15	1	93,449.15	281.05	<0.001
x_2	5854.92	1	5854.92	17.61	0.006
${x_1}^2$	35,360.36	1	35,360.36	106.35	<0.001
$x_1 \cdot x_2$	3578.67	1	3578.67	10.76	0.017
Residual	1994.99	6	332.50		
Cor Total	132,900.00	10			

The final Equation obtained from the machining energy consumption can be expressed in terms of actual factors as in Equation (14),

$$E_2 = 2949.55 - 33.00 \cdot v_c - 4851.99 \cdot f + 0.0954 \cdot {v_c}^2 + 28.26 \cdot v_c \cdot f \tag{14}$$

where E_2 is machining energy consumption (kWs).

Equation (14) shows that the lower machining energy (E_2) can be obtained by choosing higher feed and cutting speed. This result is in agreement with the previous work on the hard turning of steel that also resulted in the highest machining energy was at the lowest cutting speed and feed while the lowest machining energy was at the highest cutting speed and feed [15]. In addition, for the turning of unhardened steel (AISI 1045), it was reported that lower feed and depth of cut increases the machining energy [14].

It should be noted that the results of machining energy calculation proposed for finish hard turning of steel in this study have not been tested extensively. Nevertheless, for this particular case study where an AISI 420 martensitic stainless steel (47–48 HRC hardness), turned using a TiAlN coated carbide mounted on a particular tool holder, with parameters set at a constant depth of cut and cutting speed and feed within their particular ranges, without cutting fluid, the results are encouraging. The machining energy can be calculated and an empirical model can be developed based on the results, within the cutting speed and feed range. In addition to the cutting speed and feed themselves, the interaction between cutting speed and feed was found to affect the machining energy. This indicates that when any of the machining conditions change, the trend showed by the modified model of machining energy might change as well.

4.4. Optimum Cutting Parameters for the Case Study

Having all empirical models for surface roughness, tool life, cutting force, and machining energy consumption; optimization can be performed to determine the suitable cutting parameters that result in preferred machining responses. Some things to consider related to machining responses are:

- hard turning as a final operation must produce a smooth surface finish to meet customer demand for the geometric accuracy of machined components
- the machine shop would prefer the cutting tools to last longer
- cutting force should be low to minimize damage on the machined surface, and
- energy consumption should be minimized for each workpiece volume removed.

As mentioned above, some machining responses require contradicting cutting parameter settings. Therefore, a compromise solution is necessary to select the cutting parameters. A relatively straightforward approach that is used to optimize several responses is to overlay or superimpose the contour plots for each response. This can be performed using the Graphical Optimization function of the statistical software. Based on this approach and using Equations (11)–(14), the overlay plot as shown in Figure 5 is obtained. The criteria for optimizing the responses are then specified and incorporated into the overlay plot. As an example, if it was preferred that the surface roughness produced should be less than 0.65 µm, the coated carbide tools should last at least six minutes, the cutting force should be less than 163 N, and the machining energy consumption should be less than 280 kWs, then, the shaded, grey region represents the combinations of cutting speed and feed fulfilling the criteria specified. This region can be visually examined further to determine the appropriate operating conditions to be utilized.

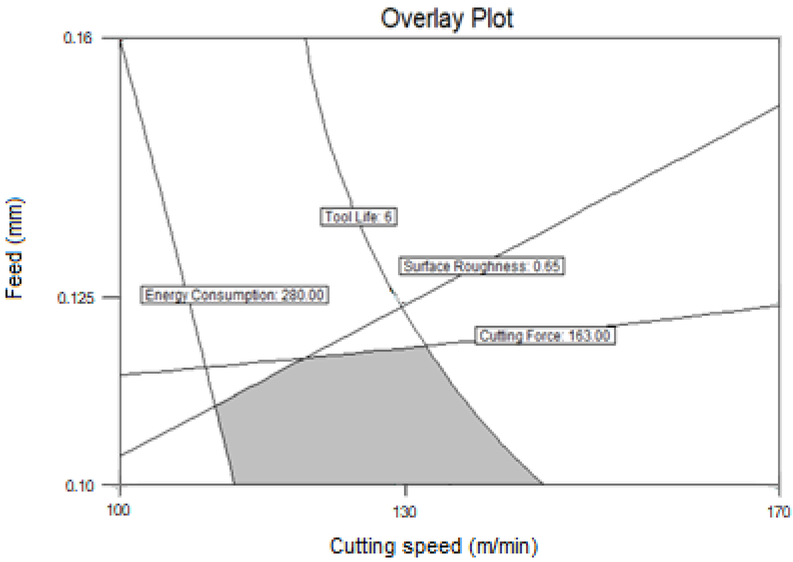

Figure 5. Overlay plot of the predetermined response criteria of T not less than 6 min, and Ra, $F_{C,}$ and E_2 of not more than 0.65 µm, 163 N, and 280 kWs, respectively.

Derringer and Suich [27] proposed another approach to optimizing several responses using the simultaneous optimization technique which makes use of the desirability functions [28]. Here, each response y_i is first converted into an individual desirability function d_i that varies over the range $0 \leq d_i \leq 1$. If the objective or target T for the response y is a maximum value then (Equation (15))

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right), & L \leq y \leq T \\ 1 & y > T \end{cases} \tag{15}$$

where L is the lower limit. On the other hand, if the objective or target T for the response y is a minimum value then (Equation (16))

$$d = \begin{cases} 1 & y < T \\ \left(\frac{U-y}{U-T}\right), & T \leq y \leq U \\ 0 & y > U \end{cases} \tag{16}$$

where U is the upper limit. The design variables are chosen to maximize the overall desirability D (Equation (17))

$$D = (d_1.d_2.d_3. \ldots .d_m)^{1/m} \tag{17}$$

where there are m responses. The overall desirability will be zero if any of the individual responses is undesirable.

The Numerical Optimization function of the statistical software can be utilized to solve the previous example using the desirability function approach. The optimization criteria for the responses are set to minimize E_2, subject to $Ra \leq 0.65$ µm, $T \geq 6$ min, and $F \leq 163$ N. Based on these criteria, the optimum cutting speed is 132.42 m/min and feed is 0.12 mm, at the desirability of 0.93. At this optimum cutting parameters, the surface roughness *Ra* is predicted to be 0.62 µm, tool life *T* is 6 min, resultant cutting force *F* is 163 N, and the machining energy E_2 will be 121 kWs.

5. Conclusions

This study proposes the use of the resultant cutting force (instead of the tangential cutting force in the conventional approach) for calculating the machining energy consumption in the finish turning process of hardened steels where typically the depth of cut is lower than the cutting tool nose radius. A case study was carried out where a hardened AISI 420 stainless steel (47–48 HRC hardness) was turned using a coated carbide tool, with a nose radius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut, 100, 130, and 170 m/min cutting speed, and 0.10, 0.125, and 0.16 mm feed. Machining responses in addition to the machining energy E_2 were surface roughness *Ra*, tool life *T*, and resultant cutting force *F*. Empirical models of the machining responses were developed using response surface methodology. The following were obtained.

1. For the cutting forces, the tangential force was lower than the radial force at some cutting parameters and the feed force is the lowest among the three force components. This is typical for finish turning.
2. The cutting speed is inversely proportional to the cutting force while the feed is proportional to the cutting force.
3. Machining energy is inversely proportional to the cutting speed and the feed. There was also an effect of the interaction between cutting speed and feed to the machining energy.
4. Comparison with another machining energy calculation approach using specific machining energy and material removal rate found the calculated machining energy using resultant cutting force proposed in this study to be similar. When the conventional approach was used where the tangential cutting force was used, the calculated machining energy will be much lower (57–70%) than the proposed approach's values.
5. Through optimization to minimize E_2, subject to $Ra \leq 0.65$ µm, $T \geq 6$ min, and $F \leq 163$ N, it was found that for the particular finish hard turning, the optimum cutting parameters were cutting speed is 132.42 m/min and feed is 0.12 mm.

Author Contributions: Conceptualization, R.N., N.M.Y., I.S., and D.K.; methodology, R.N., N.M.Y., I.S., and D.K.; formal analysis, R.N., N.M.Y., I.S., and D.K.; writing—original draft preparation, R.N., N.M.Y., and D.K.; writing—review and editing, R.N., N.M.Y., I.S., F.M.N., and D.K.; supervision, N.M.Y., I.S., and D.K.; funding acquisition, N.M.Y. and F.M.N. All authors have read and agreed to the published version of the manuscript.

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Type of manuscript: Article
Title: Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors: Rusdi Nur, M. Y. Noordin *, S. Izman, Fethma M Nor, Denni Kurniawan *
Received: 18 January 2021
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Manuscript ID	metals-1097568
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Title	Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force
Authors	Rusdi Nur , M. Y. Noordin * , S. Izman , Fethma M Nor , Denni Kurniawan *
Abstract	Downsizing energy consumption during machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. In this paper, we propose using measured cutting force to calculate power consumption during the turning process of metals. A case study was carried out where hardened stainless steel was turned using coated carbide tool without cutting fluid. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm/rev) while other parameters were kept constant. The results indicate that energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data. This generally means cutting force can be used to calculate energy consumption during the turning of metals, provided sufficient data is available. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

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Received: 18 January 2021
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> Cc: metals@mdpi.com; rusdinur@poliupg.ac.id; izman@utm.my; fethma@curtin.edu.my; Dr. Denni Kurniawan; Aaron Han
> Subject: [Metals] Manuscript ID: metals-1097568- round 22 proof
>
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>
> There are two points need you to revise.
>
> 1. Please provide the full name.
>
> 2. Reference should be cited in numerical order.
>
> Please revise it.

Kind regards,
Humphrey Wu
Section Managing Editor
E-Mail: humphrey.wu@mdpi.com
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[Metals] Manuscript ID: metals-1097568; doi: 10.3390/met11040565. Paper has been published.

1 pesan

metals@mdpi.com <metals@mdpi.com> 31 Maret 2021 15.34
Balas Ke: aaron.han@mdpi.com, metals@mdpi.com
Kepada: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn
Cc: billing@mdpi.com, website@mdpi.com, metals@mdpi.com, aaron.han@mdpi.com

Dear Authors,

We are pleased to inform you that your article "Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force" has been published in Metals and is available online:

Abstract: https://www.mdpi.com/2075-4701/11/4/565
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Rusdi Nur <rusdinur@poliupg.ac.id>

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aaron.han@mdpi.com <aaron.han@mdpi.com> 31 Maret 2021 15.44
Kepada: Denni Kurniawan <denni.kurniawan@utb.edu.bn>
Cc: Metals Editorial Office <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Dr. Kurniawan,

We are pleased to inform you that your article has been published in Metals and is available online:

Abstract: https://www.mdpi.com/2075-4701/11/4/565
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Assistant Editor

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On 2021/3/25 17:26, Metals Editorial Office wrote:

> Dear Dr. Kurniawan,
>
> We are pleased to inform you that the following paper has been officially accepted for publication:
>
> Manuscript ID: metals-1097568 Type of manuscript: Article Title:
> Determination of Energy Consumption during Turning of Hardened Stainless Steel using Cutting Force Authors:
> Rusdi Nur, M. Y. Noordin
> *, S. Izman, Fethma M Nor, Denni Kurniawan * Received: 18 January
> 2021 E-mails: rusdinur@poliupg.ac.id, noordin@utm.my, izman@utm.my, fethma@curtin.edu.my, denni.kurniawan@utb.edu.bn
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Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> 31 Maret 2021 16.12
Kepada: "aaron.han@mdpi.com" <aaron.han@mdpi.com>
Cc: Metals Editorial Office <metals@mdpi.com>, Rusdi Nur <rusdinur@poliupg.ac.id>, "M. Y. Noordin" <noordin@utm.my>, "S. Izman" <izman@utm.my>, Fethma M Nor <fethma@curtin.edu.my>

Dear Mr Han,

Thank you for the info.
Please find higher resolution of Figure 5 attached. Thank you.

Best wishes,
Denni

From: aaron.han@mdpi.com <aaron.han@mdpi.com>
Sent: 31 March 2021 3:44 PM
To: Dr. Denni Kurniawan
Cc: Metals Editorial Office; Rusdi Nur; M. Y. Noordin; S. Izman; Fethma M Nor
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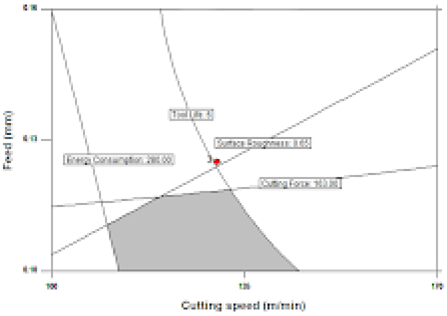
0.16
0.13
0.10
Feed (mm)
Tool Life: 5
Surface Roughness: 0.65
Energy Consumption: 280.00
Cutting Force: 163.06
100
135
170
Cutting speed (m/min)

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Article

Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force

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Abstract: Downsizing energy consumption during the machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. The manufacturing process of interest is the finish turning which has been explored to generate (near) net shapes, particularly for hardened steels. In this paper, we propose using measured cutting forces to calculate the electrical energy consumption during the finish turning process of metals where typically the depth of cut is lower than the cutting tool nose radius. In this approach, the resultant cutting force should be used for calculating the energy consumption, instead of only the main (tangential) cutting force as used in the conventional approach. A case study was carried out where a hardened stainless steel (AISI 420, hardness of 47–48 HRC) was turned using a coated carbide tool, with a nose radius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut. The experimental design varied the cutting speed (100, 130, and 170 m/min) and feed (0.10, 0.125, and 0.16 mm) while other parameters were kept constant. The results indicate that the electrical energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data as proposed. This generally means machining studies that measure cutting forces can also present energy consumption during the finish or hard turning of metals, without specifically measuring the power consumption of the machining process. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals.

Keywords: turning; cutting force; energy consumption; stainless steel

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1. Introduction

With sustainable manufacturing in mind, a product's manufacture should minimize energy consumption and negative environmental impact [1]. From the sustainable manufacturing point of view, machining is a material removal process using machine tools, where it is wasteful in its use of both material and energy [2]. Yet, given that machining can produce shapes, sizes, and surface finishes with simplicity and accuracy, it is still the most widely used manufacturing process [1,3].

Researchers have introduced models to assess the environmental impact and energy consumption of machining. Munoz et al. [4] developed modeling approaches specifically to the environmental issues of machining processes. Later on, they presented a methodology for considering environmental factors in machining facilities which used analytical process models embedded as the attributes of systems resources to determine energy use and mass flow based on process time and volume of material removed. Choi et al. [5]

developed the assessment methodology to measure the amount of the generated solid waste, the consumed energy, the incurred wastewater, and the noise level for machining processes. For energy consumption, the analytical models proposed in previous works differentiate the machine tool's energy consumption between constant and variable energy consumptions. An empirical approach was presented by Kara and Li [6] in building models for machining processes in predicting their consumed energy for each unit process. They showed that the machining process's energy consumption could be predicted using the empirical models within the set cutting parameters for the selected machine tools. Their model can calculate the energy requirement for turning or milling processes to machine a product. An on-line approach proposed by Hu et al. [7] was developed based on an energy consumption model of a machine tool for energy efficiency monitoring. Another model was proposed by He et al. [8], seeing machining in a manufacturing system, by categorizing the machine tool's energy consumption based on the task. They found that the task flow's flexibility and variability influence the machining's energy consumption in a particular manufacturing system. These models were developed to reduce environmental impact and energy consumption when machining metals.

Reducing energy consumption requires the capability of monitoring the machining process's energy consumption [9]. To better calculate the energy consumption, we need to incorporate the machining conditions into energy consumption. However, this is challenging considering the complexity of manufacturing systems and a large amount of data. Previous studies on this include automated monitoring and analysis of energy consumption in manufacturing systems using event stream processing techniques [10]. Another work by Rajemi et al. [11] includes optimization of the energy footprint of a machined product in developing the energy consumption model. As a case study, they machined a part by turning and analyzed the total consumed energy of the process. Afterward, the minimum energy footprint was determined during the optimization of the total energy consumption concerning the machine tool's tool life.

The turning process of hardened steels is gaining ground with empirical evidence that it can be done, to a certain extent, as a finishing process to get net shapes or near-net shapes of cylindrical or conical parts [12]. As a finishing process, hard turning is typically done at a low depth of cut, lower than the nose radius of the cutting tool. We identified that many works on hard turning reported the effect of machining parameters (e.g., cutting speed, depth of cut, and feed) to quantitative machining responses like cutting forces, tool life, surface roughness, and cutting temperatures. There is only a limited number of studies that are addressing the electrical energy consumption as a machining response in turning of steels, even more for hard turning. Among the few are the works of Astakhov and Xiao [13] and Li and Kara [14] in the turning of steels. These works calculated the machining energy through the measured electrical power consumption and the machining time. These works also acknowledge that power consumption can also be obtained from the multiplication of the main cutting force (i.e., tangential cutting force) and the cutting speed. The only work related to hard turning is by Chudy et al. [15] which also indirectly measured the energy as the product of the tangential cutting force, the cutting speed, and cutting time.

The simplification in calculating the machining power consumption through the use of the main cutting force only is derived from an established theory, with the assumption that the main force contributes the most to the resultant cutting force. However, we observed that the other force components other than the main cutting force are not negligible in finish hard turning. This is also true for the work on hard turning above [15], where the cutting force in the radial direction was higher than the main cutting force for some cutting parameters.

Based on these observations, in this study, we propose the use of resultant cutting force to approximate the electrical energy consumption in the hard turning of steels. As a case study, hardened stainless steel was turned under varying cutting speed and feed conditions, using a carbide tool without cutting fluid. We calculated the energy consumption and further determined the optimum machining parameters region based on the machining responses specified, which also include machining energy.

2. Cutting Forces and Energy Consumption Calculation in Finish Turning Process

The information on cutting forces during various machining processes is essential for determining machinability. Some uses of measuring cutting forces during the machining process include machining economics analysis, adaptive control applications, and numerical modeling of the machining process. As machining responses, cutting forces are studied in various machining processes. Models of cutting forces are formulated to correlate between the machining parameters to cutting forces. The empirical models are based on the established machining theory.

There are three cutting force components of the cutting force (F) in a turning process, which are designated according to the direction of the cutting tool's relative movement to the workpiece (Figure 1). The cutting force components are tangential force (F_c) in the direction of the main cutting action, radial force (F_r) in the direction toward the axis of the workpiece, and feed force (F_f) in a parallel direction to the workpiece axis [16,17].

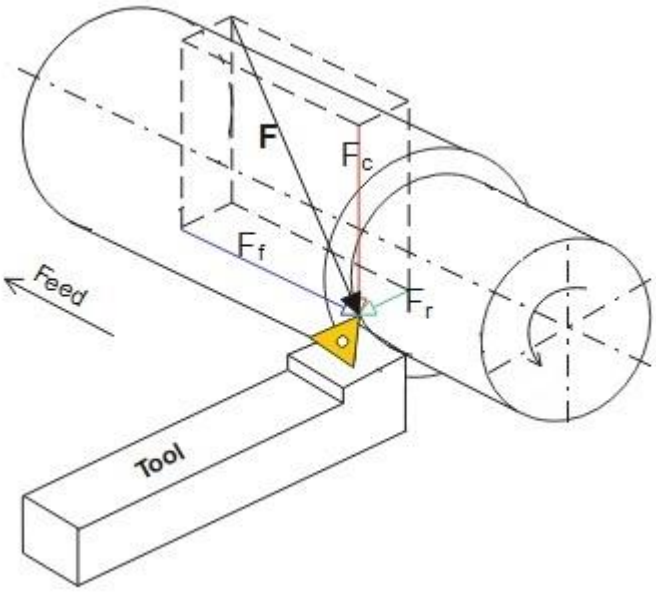

Figure 1. Cutting force components in the turning process, where F is resultant cutting force, F_c tangential force, F_r radial force, and F_f feed force.

During the turning process, power consumption can be an indicator of tool conditions and as a design criterion of the machining input. To determine the power consumption, which is calculated as the product of the cutting force and the cutting speed, only the tangential cutting force is considered for the former. This simplification was rooted in the use of orthogonal cutting theory in the relationship between machining power and cutting force. It is a common practice that tangential cutting force is used to represent the cutting force considering it makes the majority among the three force components [13,18,19].

However, we observed that for finish turning processes of steels, where the depth of cut is low—at times even lower than the nose radius of the cutting tool—the radial and feed forces are not negligible [16–18]. The feed force is indeed the lowest among the three, but its value is not that small. In some works, the radial force is even higher than the tangential cutting force for some cutting parameters [15,18]. Hence, in this study, the cutting force (F) which is the resultant of all three force components is used. It can be calculated by Equation (1),

$$P_c = v_c \cdot F \tag{1}$$

where P_c is the power consumption (W), v_c is the cutting speed (m/min), and F is the resultant cutting force (Newton).

Studies on determining the machining process's energy consumption commonly differentiate the electrical energy consumption in the idle, run-time, and production modes [10,11]. Idle mode is when the machine is ready for or in between machining. Although no material removal action is performed, there is still constant energy consumption in standby mode (for example, for the operation panel and fans). Run-time mode is when the auxiliaries are on (e.g., motor for the spindle and pump for the cutting fluid) but there is no material removal action. This consumes constant energy. Production mode is when the material removal action occurs. It varies and depends on the applied load towards the machine.

Factors that affect energy consumption include cutting parameters, cutting tools, and workpiece material [16–20]. Studies found that compared to the total energy consumption, the energy consumption during production mode where material removal action occurs is small [21,22] Considering this, efforts to lower energy consumption are focused more on reducing the constant energy. Some approaches include specific components improvement or overall cycle time reduction [5,23].

We agree with the approach proposed in a previous study [6] that the total energy consumption (E) for the turning process is a summation of the energy consumption during setup (E_1), when performing material removal (E_2), for tool change (E_3), to fabricate the cutting tool (with all its cutting edges) (E_4) and in the manufacture of the workpiece material (E_5). Considering that the workpiece material is given depending on the product and the machine shop has limited control over the energy contained in the particular workpiece material, this factor can be omitted during the machining process itself.

From the above, for the turning process, the total energy can be calculated as Equation (2),

$$E = E_1 + E_2 + E_3 + E_4 \tag{2}$$

where E_1 is the energy used during machine setup. It can be calculated as a product of the setup time and the corresponding power consumption, as shown in Equation (3),

$$E_1 = P_0 \cdot t_1 \tag{3}$$

where P_0 is the power (W) in idle and run-time modes and t_1 is the time (s) required for machine setup.

E_2 is the machining energy consumption. It is calculated by multiplying the actual machining time by the corresponding power consumption (Equation (4)) [21],

$$E_2 = \left(P_0 + k \cdot \dot{v}\right) \cdot t_2 \tag{4}$$

where k is specific machining energy (Ws/mm^3), $\dot{v}$ is material removal rate (mm^3/s) and t_2 is the accumulated material removal time of the turning process (s). In this context, t_2 can also be identified as tool life T. The value for specific machining energy k can refer to [24]. Considering Equation (1), the calculation for E_2 can also be done by using P_c which is the power of the machine tool, and acknowledging that t_2 is t_c which is the actual cutting time, making Equation (5),

$$E_2 = (P_o + P_c) \cdot t_c. \tag{5}$$

Thus, the Equation for machining energy consumption becomes Equation (6),

$$E_2 = (P_o + F \cdot v_c) \cdot t_2. \tag{6}$$

E_3 is the energy used during the replacement of a tool and is calculated as a product of the time required for tool changes and the associated power. In the turning process, tool replacement is conducted manually or using an automated tool changer, both of which occur when the tool is retracted away from the workpiece. Thus, it can be assumed that the energy used during the replacement of the tool is as much as the power when the machine is in a no-load position, which is Equation (7).

$$E_3 = P_0 \cdot t_3 \cdot \left(\frac{t_2}{T}\right) \tag{7}$$

where t_3 is the time for a replacement tool (s) and T is tool life (s), which is the same with t_2 and hence making the notation in the bracket a unity.

E_4 can be calculated as the sum of energy consumed to fabricate each cutting edge (y_E) on a cutting tool. Note that cutting tools in the form of indexable inserts usually have multiple cutting edges. So, this energy should be divided by the number of edges needed to perform the turning process (Equation (8)),

$$E_4 = y_E \cdot \left(\frac{t_2}{T}\right) \tag{8}$$

where y_E can be obtained from the total energy per insert (MJ) for material and manufacturing process and that refer to [24].

Based on the description above, the Equation to calculate the energy consumed in a turning process can be written as Equation (9),

$$E = P_0 \cdot t_1 + (P_o + F_c \cdot v_c) \cdot t_2 + P_0 \cdot t_3 + y_E \tag{9}$$

or as Equation (10),

$$E = P_0 \cdot t_1 + \left(P_0 + k \cdot \dot{v}\right) t_2 + P_0 \cdot t_3 + y_E. \tag{10}$$

Based on both Equations (9) and (10), the total energy consumption is only distinguished in the calculation of energy during the actual cutting process (E_2), which is categorized as the variable factor. Other factors, i.e., E_1, E_3, and E_4 are the same for both Equations (9) and (10) and are considered as constant factors in energy consumption calculation [6].

3. Case Study

3.1. Experimental

As a case study, a previous experiment [25] is referred to. Briefly, it is a hard turning process of stainless steel using a coated carbide tool in a two-axis CNC lathe machine rated at 5.5 kW with a varied cutting speed of 100, 130, and 170 m/min, with a varied feed of 0.1, 0.125, and 0.16 mm, and with a constant depth of cut of 0.4 mm. In determining the lower and upper values of the cutting parameters, the recommendation by the cutting tool manufacturer for finish turning a stainless steel workpiece with a hardness of up to 48 HRC was considered (ASSAB Steel, Shah Alam, Malaysia). As the depth of cut was 0.4 mm, the selected lower and upper limit values for cutting speed were 100 and 170 m/min, respectively, and for feed were 0.1 and 0.16 mm, respectively. The middle values were 130 m/min for cutting speed and 0.125 mm for feed. The turning process was performed dry (without any cutting fluid). The workpiece material was an AISI 420 martensitic stainless steel, with a chemical composition of 0.38% C, 13.6% Cr, 0.3% V, 0.9% Si, 0.5% Mn, and balance Fe (ASSAB Steel, Shah Alam, Malaysia). The stainless steel was expected to have corrosion resistance, stability at a hardened state, and to result in a fine surface finish for plastic mold applications. The stainless steel was hardened throughout by heat treatment to reach a hardness value of 47–48 HRC. Before the machining trial, the workpiece surface was finish turned using the last set of cutting parameters. The cutting tool used for the experiment was a TiAlN coated carbide tool (Kennametal, Shah Alam, Malaysia) that is designated as CNMG 120408. The cutting tool was a fine-grained WC-6% Co substrate coated with 3.0 to 35 m thick TiAlN through physical vapor deposition. The cutting tool was mounted on a holder with an ISO designation of MCLNL 1616-H12, giving the 10° rake angle, −5° side cutting edge angle, and 5° relief angle. The positive rake angle—commonly hard turning sets negative rake angle—was due to the tool has a 15° chip breaker profile, despite the tool holder actually positions the cutting tool at $-5°$ angle. The tool wear was measured according to ANSI/ASME B94.55M-1985 standard, subjected to the maximum flank wear width (V_{Bmax}) within the nose radius of the tool (zone C). An optical microscope (Stemi 200-C, Carl Zeiss, Petaling Jaya, Malaysia) with an image analyzer was used for this purpose. Surface roughness (Ra) was measured by a surface profilometer (Accretech Handysurf, Tokyo Seimitsu, Tokyo, Japan) at 0.8 mm cut off length and 4 mm sampling length in each measurement. The tool life criteria were at a maximum of 0.14 mm of flank wear width, at the machined surface roughness Ra beyond 1.6 µm, or severely damaged cutting tool.

The experiments measured the cutting force elements in all three directions (F_c, F_r, and F_f is the schematic layout below (Figure 2). A three-component turning dynamometer (Kistler, Type 9265B, Singapore) with data acquisition software was used for this purpose. For measuring the electrical power consumption of the turning process, three portable power monitors (Omron ZN-CTX21, Johor Bahru, Malaysia) with three clamp meters (Omron ZNCTM11, Johor Bahru, Malaysia) were used. One power monitor was used to measure the main power while the other two to the spindle and axis drives. The measured power data was acquired and visualized using Wave Inspire ES (Omron, Johor Bahru, Malaysia) software.

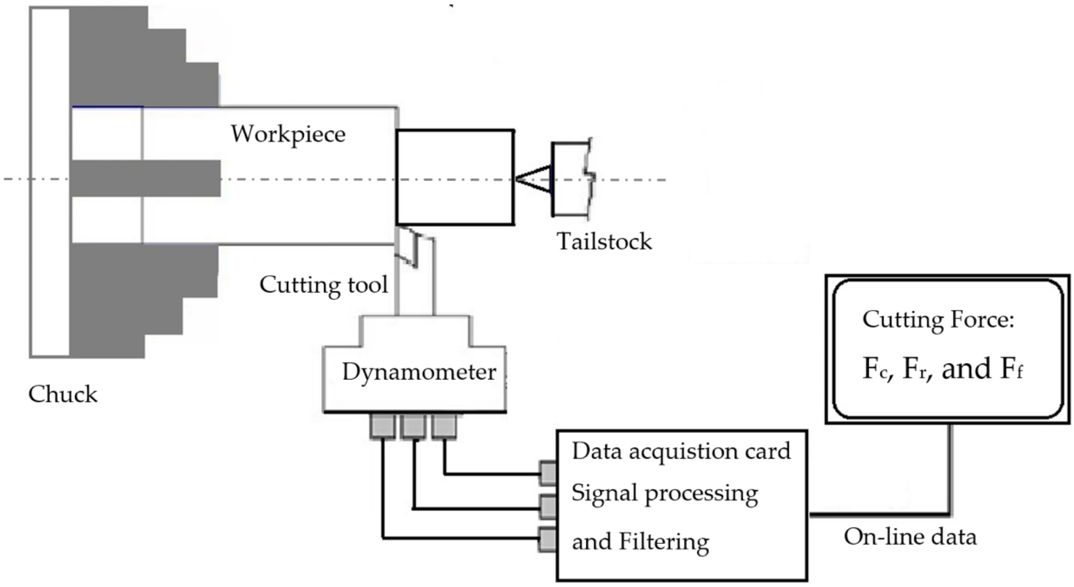

Figure 2. Schematic layout of cutting force measurement setup.

3.2. Experimental Design

Response Surface Methodology (RSM) was chosen for the design of experiments. A commercial software (Design Expert, StatEase, Minneapolis, MN, USA) was used for this purpose. For the RSM, regression is used to approximate the machining response based on the relationship between one or more factors (input variable) and the estimated response, y_{est}. The fitting of the model Equation was using the least square technique through residual error minimization. The model Equation and its coefficients were tested for statistical significance. Analysis of variance (ANOVA) was used for this purpose. For the case at hand, a three-level factorial design having two input factors and 2 center points was applied, making 11 runs in total (Table 1). The type 1 error (α) value was set at 0.05 for the models and its coefficients to be considered significant.

Table 1. Factor and levels for the experiments.

Factor	Coded Form		
	−1	0	1
x_1–cutting speed (m/min)	100	130	170
x_2–feed (mm)	0.10	0.125	0.16

4. Results and Discussion

4.1. Surface Roughness and Tool Life

The experimental results for surface roughness and tool life for all eleven trials are summarized in Table 2 [25].

Table 2. Experimental results for surface roughness and tool life. (Note: v_c is cutting speed, f feed, Ra surface roughness, and T tool life).

v_c (m/min)	f (mm)	Ra (μm)	T (min)
100	0.10	0.60	30.50
130	0.10	0.54	8.84
170	0.10	0.47	3.93
100	0.125	0.87	19.20
130	0.125	0.73	5.50
170	0.125	0.50	3.90
100	0.16	0.92	15.00
130	0.16	0.78	4.65
170	0.16	0.74	2.50
130	0.125	0.42	5.18
130	0.125	0.68	7.00

Based on the results of surface roughness and tool life, a selection of models using regression calculations were made [26]. The linear model was chosen for modeling the surface roughness while the quadratic model was most suitable for the tool life. The backward elimination procedure was selected to automatically reduce the terms that are not significant and the resulting ANOVA table for the reduced linear model for surface roughness and the reduced quadratic model for tool life is displayed in Table 3 [25]. The ANOVA table shows the statistics used to test the hypotheses about the population means.

Table 3. Result of ANOVA table for tool life and surface roughness.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Value	p Value
Surface roughness					
Model	0.19	2	0.095	8.94	0.009
x_1	0.07	1	0.07	6.8	0.031
x_2	0.12	1	0.12	11.13	0.01
Residual	0.09	8	0.01		
Cor Total	0.28	10			
Tool Life					
Model	5.73	3	1.91	104	<0.001
x_1	4.92	1	4.92	267.93	<0.001
x_2	0.53	1	0.53	28.99	0.001
${x_1}^2$	0.57	1	0.57	31.27	0.008
Residual	0.13	7	0.018		
Cor Total	5.86	10			

In an analysis of variance, the total variation in the response measurements, in this case, the surface roughness and tool life values, are partitioned into variation which can be explained by the independent variables or factor effects (Model) and the variation which is not explained by the independent variables (Residual which is also called Error). In the case of surface roughness, the model is made up of the main effects of cutting speed, x_1, and feed, x_2. Thus, the Sum of Squares for the independent variables, x_1 and x_2, add up to become the Sum of Squares for Model. Whilst the Sum of Squares for Model and Residual add up to the Total Variance.

Degrees of freedom are associated with the sources of variance. The total variance has N-1 degrees of freedom, where N is the total number of experiments. In this case, there were $N = 11$ experiments, so the degrees of freedom for total is 10. The degrees of freedom for the model is the sum degrees of freedom of the independent variables or factor effects which explains the variation. In the case of independent variables or factor effects, the degrees of freedom for each independent variable or factor effect is the number of levels -1. Thus, for cutting speed, the degrees of freedom is $2 - 1 = 1$ and this is similar to the degrees of freedom for feed. The degrees of freedom for the model is therefore $1 + 1 = 2$. The degrees of freedom residual is the degrees of freedom total minus the degrees of freedom model, which is $10 - 2 = 8$. The respective Mean squares are computed by dividing the respective Sum of squares by their respective degrees of freedom. The respective F ratios are computed by dividing the respective Mean squares by the Mean square residual or error and these are used to test the significance of the predictors in the model. The p-value associated with these F values are small, 0.031 or less. The p value is compared to the alpha level (typically 0.05) and, if it is smaller, then the independent variable or factor effects is statistically significant. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted thus indicating differences in the mean values of the respective independent variables or factor effects.

The final equation, in terms of actual factors, acquired from the model for surface roughness is as in Equation (11),

$$Ra = 0.4793 - 0.0031 \cdot v_c + 4.6513 \cdot f \tag{11}$$

where Ra is surface roughness (μm), v_c *is* cutting speed (m/min), and f is feed (mm/rev).

For tool life, the logarithmic transformation is recommended based on the best lambda value found at the minimum point of the Box–Cox curve generated by the natural log of the sum of squares of the residuals. The final equation, in terms of actual factors, achieved from the model for tool life can be expressed as in Equation (12),

$$Ln\ T = 13.4177 - 0.1297 \cdot v_c - 9.8739 \cdot f + 0.0004 \cdot {v_c}^2 \tag{12}$$

where T is tool life (min) and the other variables were as defined previously.

4.2. Cutting Force

The experimental results for cutting force and the respective calculated machining energy for all trials are summarized in Table 4. The machining time t_2 is the tool life in second. F is the resultant cutting force calculated from the measured tangential force F_c, radial force F_r, and feed force F_f. The trend in cutting force values where the feed force is the lowest among the three force components and where the radial force is higher than the tangential force at some cutting parameters is in agreement with previous work on the hard turning of AISI 5140 (55 ± 1 HRC hardness) using CBN (cubic boron nitride) tool at 150–300 m/min cutting speed, 0.05–0.2 mm feed, and 0.2 mm depth of cut [15].

Table 4. Experimental results for cutting force and machining energy. (Note: v_c is cutting speed, f feed, t_2 tool life (in second), F_c tangential force, F_r radial force, F_f feed force, F resultant cutting force, E_2 calculated machining energy based on Equation (6), and $E_2{}^{\#}$ calculated machining energy based on Equation (4)).

v_c (m/min)	f (mm)	t_2 (s)	F_r (N)	F_c (N)	F_f (N)	F (N)	E_2 (kWs)	$E_2{}^{\#}$ (kWs)
100	0.10	1830	103	80	39	136.12	417.11	428.93
130	0.10	530.4	100	75	38	130.65	152.07	162.81
170	0.10	235.8	96	73	35	125.58	85.82	95.46
100	0.125	1152	128	110	44	174.41	336.80	337.93
130	0.125	330	125	115	42	174.97	127.03	127.05
170	0.125	234	123	100	41	163.74	110.48	117.95
100	0.16	900	127	124	45	183.11	276.59	337.93
130	0.16	279	118	120	43	173.70	106.93	137.33
170	0.16	150	114	118	41	169.12	73.80	97.13
130	0.125	310.8	120	106	40	165.03	111.13	119.77
130	0.125	420	124	113	43	173.19	112.84	161.18

The model selection and its subsequent reduction as well as the empirical Equation development for cutting force were performed in the same manner as those for surface roughness and tool life [25]. The resulting ANOVA is as shown in Table 5.

Table 5. Result of ANOVA for cutting force F.

Source	Sum of Square	Degrees of Freedom	Mean Square	F Value	p Value
Model	3988.78	3	1329.59	134.33	<0.001
x_1	205.99	1	205.99	20.81	0.003
x_2	594.82	1	594.82	60.10	<0.001
$x_2{}^2$	1154.27	1	1154.27	116.62	<0.001
Residual	69.29	7	9.90		
Cor Total	4058.06	10			

The final Equation obtained from the model for cutting force can be expressed in terms of actual factors as in Equation (13),

$$F = -299.88 - 0.17{\cdot}v_c + 6895.59{\cdot}f - 23667.19{\cdot}f^2 \quad (13)$$

where F is the resultant cutting force (N).

The final model Equation for cutting force can be shown as a 3D contour graph (Figure 3). From Equation (13) and Figure 3, it can be observed that the cutting force is affected significantly first by the feed and second by the cutting speed. Generally, the feed is proportional to the cutting force while the cutting speed is inversely proportional to the cutting force. The proportionality relation between feed and cutting force is as expected since feed increase means the higher surface area of the workpiece to machine by the cutting tool [25]. The finding on cutting speed effect to cutting force was analyzed to be due to the higher cutting temperature at high cutting speed softened the workpiece and there was a transition from low to high cutting speed indicated by the change in chip type from continuous to segmented [25].

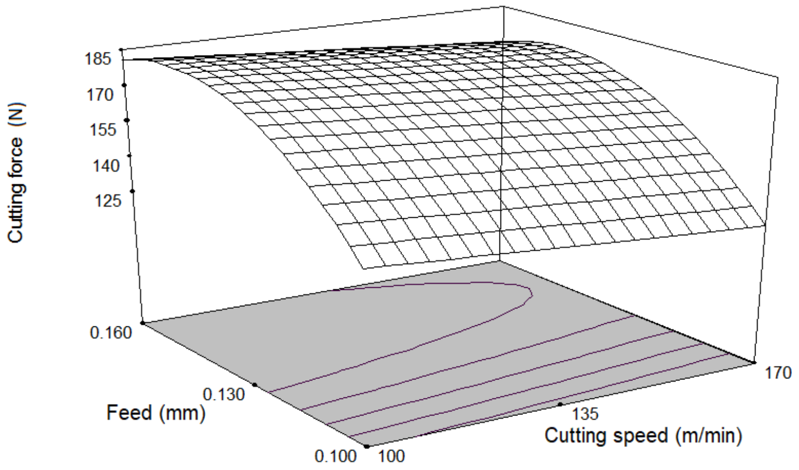

Figure 3. Response surface graph of 3D surface for *F*.

4.3. Energy Consumption

The maximum energy for the turning process (E_2) was calculated using cutting force data, as in Equation (6). The power consumption in idle and run-time modes P_0 was measured to be 1925 W. The maximum energy for the turning process, E_2, of 417.11 kWs was shown by the lowest of cutting speed and feed, while the minimum energy for the machining process (73.8 kWs) for cutting speed and feed rate is high (Figure 4). We calculated that E_1, E_3, and E_4 were 3.85 kWs, 5.58 kWs, and 1325 kWs, respectively. Compared to the total machining energy, the actual machining energy E_2 is low (5–20% of total energy), in agreement with a previous study [21,22].

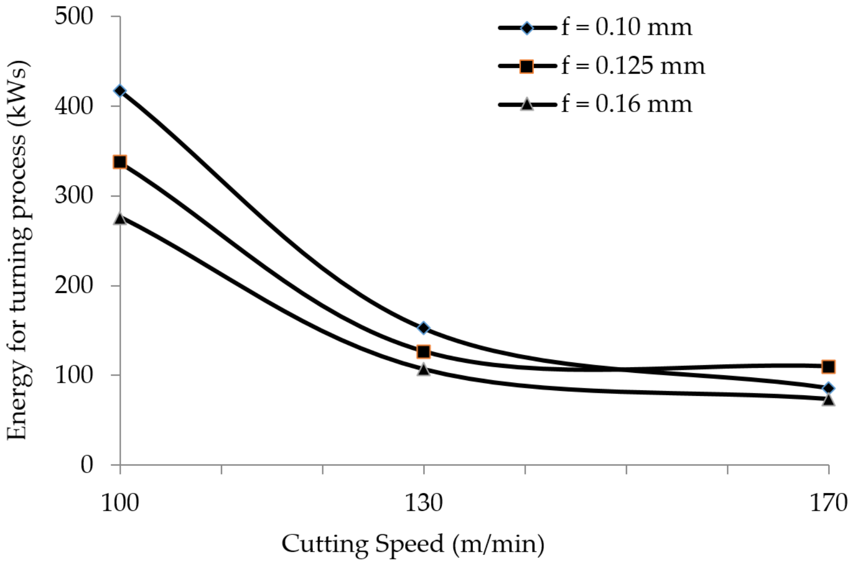

Figure 4. Energy for turning process (E_2) at various cutting speeds and feed.

For comparison, we also calculated E_2 using Equation (4), with specific machining energy k 3.5 Ws/mm^3 and material removal rate $\dot{v}$ (in mm^3/s) calculated by multiplying cutting speed, feed, and depth of cut. We found that the values are comparable with the machining energy E_2 calculated using resultant cutting force as proposed in this study. Had the tangential cutting force was used like in the conventional approach instead of resultant cutting force, the calculated machining energy E_2 will be 57–70% of the calculated values in this study.

The quadratic model was chosen to represent the data of E_2 because it has the least probabilistic value. ANOVA of the selected regression model and its coefficients was performed (Table 6).

Table 6. ANOVA for machining energy consumption (E_2).

Source	Sum of Square	Degrees of Freedom	Mean Square	*F* Value	*p* Value
Model	130,900.00	4	32,715.34	98.39	<0.001
x_1	93,449.15	1	93,449.15	281.05	<0.001
x_2	5854.92	1	5854.92	17.61	0.006
${x_1}^2$	35,360.36	1	35,360.36	106.35	<0.001
$x_1 \cdot x_2$	3578.67	1	3578.67	10.76	0.017
Residual	1994.99	6	332.50		
Cor Total	132,900.00	10			

The final Equation obtained from the machining energy consumption can be expressed in terms of actual factors as in Equation (14),

$$E_2 = 2949.55 - 33.00 \cdot v_c - 4851.99 \cdot f + 0.0954 \cdot {v_c}^2 + 28.26 \cdot v_c \cdot f \tag{14}$$

where E_2 is machining energy consumption (kWs).

Equation (14) shows that the lower machining energy (E_2) can be obtained by choosing higher feed and cutting speed. This result is in agreement with the previous work on the hard turning of steel that also resulted in the highest machining energy was at the lowest cutting speed and feed while the lowest machining energy was at the highest cutting speed and feed [15]. In addition, for the turning of unhardened steel (AISI 1045), it was reported that lower feed and depth of cut increases the machining energy [14].

It should be noted that the results of machining energy calculation proposed for finish hard turning of steel in this study have not been tested extensively. Nevertheless, for this particular case study where an AISI 420 martensitic stainless steel (47–48 HRC hardness), turned using a TiAlN coated carbide mounted on a particular tool holder, with parameters set at a constant depth of cut and cutting speed and feed within their particular ranges, without cutting fluid, the results are encouraging. The machining energy can be calculated and an empirical model can be developed based on the results, within the cutting speed and feed range. In addition to the cutting speed and feed themselves, the interaction between cutting speed and feed was found to affect the machining energy. This indicates that when any of the machining conditions change, the trend showed by the modified model of machining energy might change as well.

4.4. Optimum Cutting Parameters for the Case Study

Having all empirical models for surface roughness, tool life, cutting force, and machining energy consumption; optimization can be performed to determine the suitable cutting parameters that result in preferred machining responses. Some things to consider related to machining responses are:

- hard turning as a final operation must produce a smooth surface finish to meet customer demand for the geometric accuracy of machined components
- the machine shop would prefer the cutting tools to last longer
- cutting force should be low to minimize damage on the machined surface, and
- energy consumption should be minimized for each workpiece volume removed.

As mentioned above, some machining responses require contradicting cutting parameter settings. Therefore, a compromise solution is necessary to select the cutting parameters. A relatively straightforward approach that is used to optimize several responses is to overlay or superimpose the contour plots for each response. This can be performed using the Graphical Optimization function of the statistical software. Based on this approach and using Equations (11)–(14), the overlay plot as shown in Figure 5 is obtained. The criteria for optimizing the responses are then specified and incorporated into the overlay plot. As an example, if it was preferred that the surface roughness produced should be less than 0.65 µm, the coated carbide tools should last at least six minutes, the cutting force should be less than 163 N, and the machining energy consumption should be less than 280 kWs, then, the shaded, grey region represents the combinations of cutting speed and feed fulfilling the criteria specified. This region can be visually examined further to determine the appropriate operating conditions to be utilized.

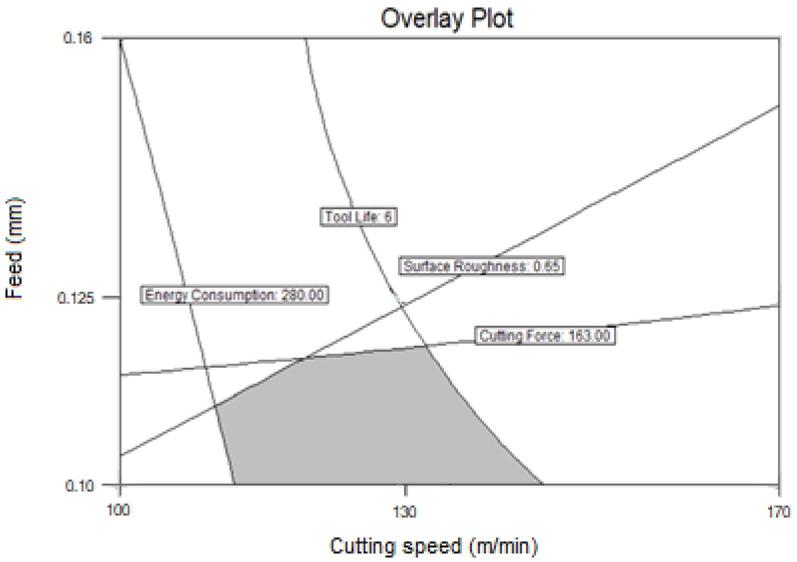

Figure 5. Overlay plot of the predetermined response criteria of T not less than 6 min, and Ra, $F_{C,}$ and E_2 of not more than 0.65 µm, 163 N, and 280 kWs, respectively.

Derringer and Suich [27] proposed another approach to optimizing several responses using the simultaneous optimization technique which makes use of the desirability functions [28]. Here, each response y_i is first converted into an individual desirability function d_i that varies over the range $0 \leq d_i \leq 1$. If the objective or target T for the response y is a maximum value then (Equation (15))

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right), & L \leq y \leq T \\ 1 & y > T \end{cases} \tag{15}$$

where L is the lower limit. On the other hand, if the objective or target T for the response y is a minimum value then (Equation (16))

$$d = \begin{cases} 1 & y < T \\ \left(\frac{U-y}{U-T}\right), & T \leq y \leq U \\ 0 & y > U \end{cases} \tag{16}$$

where U is the upper limit. The design variables are chosen to maximize the overall desirability D (Equation (17))

$$D = (d_1.d_2.d_3. \ldots .d_m)^{1/m} \tag{17}$$

where there are m responses. The overall desirability will be zero if any of the individual responses is undesirable.

The Numerical Optimization function of the statistical software can be utilized to solve the previous example using the desirability function approach. The optimization criteria for the responses are set to minimize E_2, subject to $Ra \leq 0.65$ µm, $T \geq 6$ min, and $F \leq 163$ N. Based on these criteria, the optimum cutting speed is 132.42 m/min and feed is 0.12 mm, at the desirability of 0.93. At this optimum cutting parameters, the surface roughness Ra is predicted to be 0.62 µm, tool life T is 6 min, resultant cutting force F is 163 N, and the machining energy E_2 will be 121 kWs.

5. Conclusions

This study proposes the use of the resultant cutting force (instead of the tangential cutting force in the conventional approach) for calculating the machining energy consumption in the finish turning process of hardened steels where typically the depth of cut is lower than the cutting tool nose radius. A case study was carried out where a hardened AISI 420 stainless steel (47–48 HRC hardness) was turned using a coated carbide tool, with a nose radius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut, 100, 130, and 170 m/min cutting speed, and 0.10, 0.125, and 0.16 mm feed. Machining responses in addition to the machining energy E_2 were surface roughness Ra, tool life T, and resultant cutting force F. Empirical models of the machining responses were developed using response surface methodology. The following were obtained.

1. For the cutting forces, the tangential force was lower than the radial force at some cutting parameters and the feed force is the lowest among the three force components. This is typical for finish turning.
2. The cutting speed is inversely proportional to the cutting force while the feed is proportional to the cutting force.
3. Machining energy is inversely proportional to the cutting speed and the feed. There was also an effect of the interaction between cutting speed and feed to the machining energy.
4. Comparison with another machining energy calculation approach using specific machining energy and material removal rate found the calculated machining energy using resultant cutting force proposed in this study to be similar. When the conventional approach was used where the tangential cutting force was used, the calculated machining energy will be much lower (57–70%) than the proposed approach's values.
5. Through optimization to minimize E_2, subject to $Ra \leq 0.65$ µm, $T \geq 6$ min, and $F \leq 163$ N, it was found that for the particular finish hard turning, the optimum cutting parameters were cutting speed is 132.42 m/min and feed is 0.12 mm.

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