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Optimization of Machining Parameters In Turning Process Using Exergy Analysis

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Abstract

This study uses thermodynamic frame work to conceptualize the energy used in a manufacturing process. High amount of energy consumed per unit material removed in traditional process has formed the base for developing new technologies while, optimizing the traditional method is often neglected. The main focus has been on product quality while the efficiency of energy per material removal has taken a back step. The study covers turning operation and characterizes the energy consumption by varying the machining parameters. With a steep increase in energy prices, a major part of machining cost is due to the energy consumed. Therefore we take this opportunity to perform exergy analysis to identify conditions where resources are lost and thereby arrive at optimum conditions where the process can run at higher efficiency and reduced cost.

Keywords: exergy analysis, chemical exergy, energy, degree of perfection, turning process, design of experiments,

Introduction

Manufacturing involves conversion of raw materials into useful products through consumption of energy and other resources. Turning is a material removal process with a single point cutting tool moving parallel to the axis of rotation of the job. A thermodynamic framework using exergy analysis is performed to analyse the usefulness of the final product with respect to the energy and resources consumed for the transformation and thereby arrive at optimum operating conditions. The thermodynamic framework is developed upon exergy analysis [1]. The process is modelled as an open thermodynamic system with mass flow, heat and work interactions between the system and the surrounding [2]. The data has been collected from previous work in turning and also includes numerous values and calculations based on our experiments. The major studies from literature are, for energy consumption in manufacturing by various authors are cited in [3], [4], [5], [6],[7],[8]energy consumption in turning process W. Li [9], model on cutting forces by W. J. Endres [10], design of experiment by L. Condra [11], design of experiment in Taguchi method by W. H. P yang [12], the model of chemical exergy is derived by Sato [13], chemical exergy of basic elements is taken from the work of R. Rivero [14], properties of reference environment degree of perfection and cumulative exergy by J. Szargut [15][16][17]. Apart from this, several researchers are working on thermodynamic reference states which can be used with the model presented here. This approach is further extended to other traditional operations like milling[18], drilling[19] etc. Exergy analysis can also be done in manufacturing process such as casting[20], forging[21] which involves phase change,

Experimental Setup and Measurement Technique

The experiment is performed on a lathe with the following specification:

Manufacturer: The Mysore Kirloskar Limited
Model: Turnmaster 35
Admit between centres: 800 mm
Swing overbed: 175 mm
Spindle bore: 40 mm
Number of spindle speeds: 8
Speed range: 45 – 1120 Rpm
Feed range: 0.18 to 0.63 mm/rev
Motor power: 2.2 kw

The cutting speed (V) is the characteristic of the material being cut and the cutting tool. Mild steel being the most widely used material in industry is chosen for our experiment. Carbide cutting tool is chosen. The diameter (D) of job for the experiment is 50mm. The RPM (N) range is determined from the cutting speed using the formula

$$N = \frac{V \times 60}{\pi \times D}$$

The RPM value corresponding to the standard RPM in the machine is chosen. Cutting speed is a function of feed rate. The RPM is calculated for all values of feed and corresponding cutting speed. By varying the three parameters in depth of cut (DOC), RPM and feed rate, a large number of experimental combinations are obtained. The Design of Experiment (DOE) is performed to reduce the number of experiments. We have adopted Taguchi technique to limit the experiment to the most significant of the parameter combinations. Thus factors that do not contribute to the variation are controlled effectively. A process modelled with this technique is found to produce a more consistent output. The number of experiments for the combinations has been effectively limited to 22. We have used Minitab version 17.0 (developed by minitab.Inc) to design Taguchi for our experiment.

Table 1 is the list of runs obtained on simulating the Taguchi design using Minitab software.

The process is framed as an open system with mass and work interactions. The mass flow is material removed after conversion whereas the work flow is the energy used in conversion and the corresponding usefulness of the product. The input to the system is the electrical power (P) in terms of current (I), voltage (V). A multimeter is connected to the source to measure I and V.

$$P = V \times I$$

The optimal parameter condition could be achieved when the power consumed per unit material removal rate (Y) is minimal but this would be incomplete to conclude without calculating the exergy for the process and the corresponding degree of perfection. M_r is mass of material removed in time (T_{s}).

$$Y = \frac{P}{M_r \times T_s}$$

Table 1: List of Experiments Simulated Through Taguchi Design

Speed (Rpm)	**Feed (mm/rev)**	**DOC (mm)**
280	0.4	0.5
280	0.5	1
280	0.63	1.5
450	0.4	1
450	0.5	1
450	0.63	0.5
710	0.4	0.8
710	0.5	0.5
710	0.63	1
450	0.25	0.5
450	0.355	0.75
450	0.5	0.8
710	0.25	1
710	0.355	1.5
710	0.5	0.5
1120	0.25	0.75
1120	0.355	0.5
1120	0.5	1
710	0.18	0.1
710	0.2	0.5
1120	0.18	0.5
1120	0.2	0.1

Table 2: Experimental Values

Speed	**Feed**	**DOC**	**V**	**I**	**P**	**M_r**	**T_s**	**T_d**
RPM	mm/rev	mm	V	A	W	kg	s	ºC
280	0.4	0.5	335	0.63	211.05	0.046	70	2
280	0.5	1	385	0.75	288.75	0.079	68	4
280	0.63	1.5	326	0.95	309.7	0.11	54	10
450	0.4	1	476	0.95	452.2	0.131	46	15
450	0.5	1	445	0.93	413.85	0.079	36	11
Speed	**Feed**	**DOC**	**V**	**I**	**P**	**M_r**	**T_s**	**T_d**
RPM	mm/rev	mm	V	A	W	kg	s	ºC
450	0.63	0.5	408	0.85	346.8	0.04	28	9
710	0.4	0.8	410	0.81	332.1	0.064	35	16
710	0.5	0.5	356	0.75	267	0.048	25	15
710	0.63	1	380	1.18	448.4	0.033	16	14
450	0.25	0.5	390	1.46	569.4	0.04	61	5
450	0.355	1	426	1.93	822.18	0.067	42	8
450	0.5	1	376	2.44	917.44	0.041	30.86	13
710	0.25	1	342	2.11	721.62	0.026	37.84	15
710	0.355	1.5	346	2.31	799.26	0.038	35	16
710	0.5	0.5	335	2.82	944.7	0.038	26	11
1120	0.25	0.75	408	2.65	1081.2	0.04	22	13
1120	0.355	0.5	397	3.31	1314.07	0.036	15	13
1120	0.5	1	399	3.5	1396.5	0.044	12	16
710	0.18	0.1	397	1.12	444.64	0.032	29	10
710	0.2	0.5	356	2.8	996.8	0.044	51	10
1120	0.18	0.5	386	2.63	1015.18	0.029	31	13
1120	0.2	0.1	380	2.18	828.4	0.011	29	12

Table 3: Power Consumption Per Material Removal Rate

Speed	**Feed**	**DOC**	**Y**
RPM	mm/rev	mm	
280	0.4	0.5	4.58
280	0.5	1	3.65
280	0.63	1.5	2.8
450	0.4	1	3.45
450	0.5	1	5.23
450	0.63	0.5	8.67
710	0.4	0.8	5.18
710	0.5	0.5	5.5625
710	0.63	1	13.58
450	0.25	0.5	14.235

450	0.355	1	12.27
450	0.5	1	22.37
710	0.25	1	27.754
710	0.355	1.5	21
710	0.5	0.5	24.8
1120	0.25	0.75	27.03
1120	0.355	0.5	36.5
1120	0.5	1	31.72
710	0.18	0.1	14.65
710	0.2	0.5	22.65
1120	0.18	0.5	35
1120	0.2	0.1	75.3

Exergy exists whenever the state of the system is different from its reference state or the state of the surroundings. The temperature and pressure gradient contribute to the physical exergy while the composition gradient contribute to the chemical exergy. The exergy is the sum of physical and chemical exergy.

The input exergy is from the mass of work piece and electricity ($B_{total-in}$). Exergy due to mass is calculated from knowing the composition ($B_{in-mass}$). Spectral analysis of the work piece was done and the composition is tabulated in Table 4.

Table 4: Composition of Mild Steel

Fe	98.24 %
C	0.089 %
Si	0.021 %
Mn	1.201 %
P	0.012 %
S	0.215 %
Cr	0.018 %
Mo	0.027 %
Ni	0.001 %
Al	0.001 %
Cu	0.002 %
Ti	0.003 %
V	0.010 %
W	0.002 %
Pb	0.159 %

The second law efficieny of the turning process is calculated using the exergy in the raw material (B_{in}) and exergy in the finished product (B_{out}). The second law efficiency is defined as degree of perfection as per [15].

$$\eta = \frac{B_{out}}{B_{in}}$$

The chemical exergy of the mass is based on the number of moles it contains. Hence molar chemical exergy depends on the molar fraction of every component in the work piece and its difference with the reference state. The specific chemical exergy of various metals is given in the Table 5.

$M_{work\ piece}$ is the mass of the work piece before machining. Knowing these details, we calculated the number of moles of each element and then we have calculated the chemical exergy for each element (M_x) and sum it up to get the total chemical exergy.

Table 5: Standard Chemical Exergy

Substance	State	Molecular Mass M	Enthalpy of devaluation	Std Chemical Exergy
		kg/kmol	D^o,kj/mol	$e^o_{x,ch}$, kj/mol
Al	S	26.98	930.9	795.7
Fe	s. α	55.847	412.12	374.3
C	s. graphite	12.011	393.509	409.87
Si	S	28.086	910.94	854.9
Mn	s. α	54.938	520.03	487.7
P	s. α, white	30.974	840.06	861.4
S	s. rhombic	32.064	725.42	609.6
Cr	S	51.996	569.86	584.7
Ni	S	58.710	239.74	232.7
Cu	S	63.540	201.59	134.2
W	S	183.85	842.87	827.5
Pb	S	207.20	305.64	232.8

$$M_x = M_{work\ piece} \times (\%composition)$$

$$No\ of\ moles = \frac{molecular\ weight}{M_x}$$

$$B_{in-mass} = Specific\ chemical\ exergy \times No\ of\ moles$$

$$B_{Total-in} = B_{in} + P$$

Exergy of the finished product ($B_{total-out}$) is calculated similarly with respect to the mass of the finished product (M_{-out}). The electrical power is Zero in case $B_{total-out.}$

Result and Discussion

The energy consumed per unit material removed is calculated for different machining parameters. Since the experiments were done using Taguchi technique, Y has to be expressed in S-N ratio (Signal to Noise ratio).

$$SN\ ratio = -10log\frac{\sum_{i=1}^{n} y_i^2}{n}$$

n=number of experiments per condition (3).

Factorial effects graphs are plotted with SN ratio against speed (rpm) Figure 1, DOC Figure 2 and feed rate Figure 3.

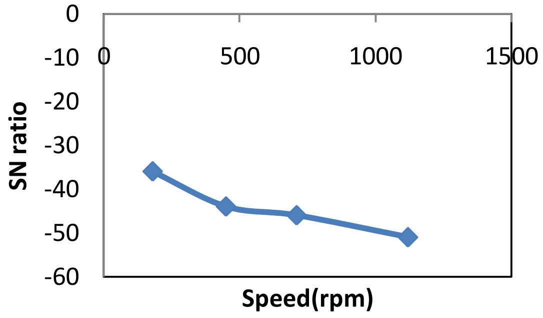

Figure 1: Speed (RPM) As A Function of SN Ratio

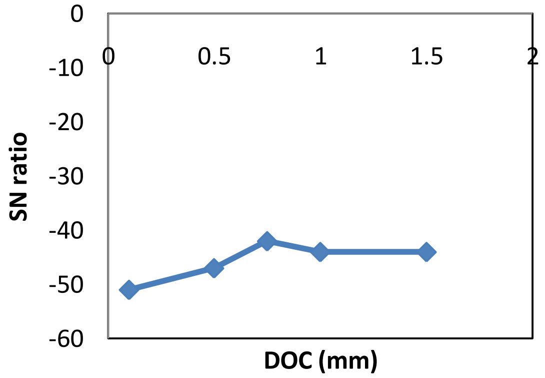

Figure 2: DOC As A Function of SN Ratio

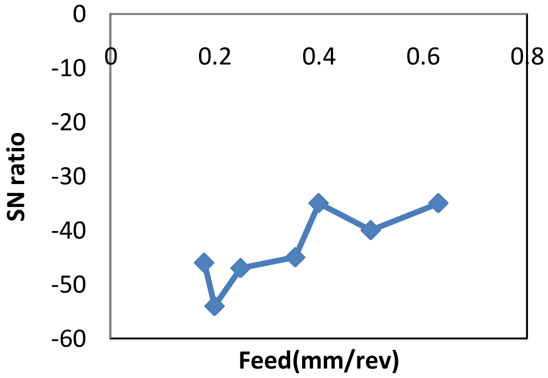

Figure 3: Feed As A Function of SN Ratio

The lowest value of Y is better but it doesn’t refer to the best combination of machining parameters as second law efficiency (degree of perfection) is not considered. The exergy balance equation is employed to derive the second law efficiency in terms of exergy. The total exergy in and total exergy out of the system are calculated for all combinations of machining parameters. The degree of perfection is calculated for every experiment and tabulated in Table 6.

The degree of perfection obtained through second law efficiency of exergy analysis helps in determining the closeness of the process to the ideal process. The average degree of perfection of turning process is found to be 98%. This is possible because turning operation doesn’t involve exergy loss due to phase change.

The optimal machining parameters obtained through energy analysis and energy consumed per material removal rate are speed = 450 rpm, DOC = 1mm, Feed = 0.4mm/rev. However this condition is least efficient when compared to the results obtained from second law efficiency through exergy analysis. The inputs for degree of perfection are obtained from the energy equation and exergy balance equation involving physical and chemical exergies. The machining parameters with maximum degree of perfection are speed = 1120 rpm, DOC = 0.1 mm and Feed = 0.2 mm/rev.

Table 6: Degree of Perfection

Run	**Speed**	**Feed**	**DOC**	**Power**	**M-$_{out}$**	**M $_{–in}$**	**B$_{in}$ – mass**	**B$_{in}$ - total**	**B$_{out}$**	**Efficiency**
	RPM	**mm/rev**	**mm**	**W**	**kg**	**kg**	**MJ**	**MJ**	**MJ**	**%**
1	280	0.4	0.5	211.05	4.784	4.83	32.64	32.65	32.33	99.00
	280	0.5	1	288.75	4.705	43784	32.33	32.35	31.79	98.28
	280	0.63	1.5	309.7	4.595	4.705	31.79	31.81	31.05	97.61
	450	0.4	1	452.2	4.251	4.382	29.69	29.63	28.72	96.94
	450	0.5	1	413.85	4.382	4.461	30.14	30.16	29.61	98.18
	450	0.63	0.5	346.8	4.461	4.501	30.41	30.42	30.14	99.07
	710	0.4	0.8	332.1	4.187	4.251	28.72	28.74	28.29	98.45
	710	0.5	0.5	267	4.139	4.187	28.29	28.30	27.97	98.83
	710	0.63	1	448.4	4.106	4.139	27.97	27.97	27.74	99.17
2	450	0.25	0.5	569.4	4.792	4.832	32.65	32.69	32.38	99.06
	450	0.355	0.75	822.18	4.725	4.792	32.38	32.42	31.93	98.49
	450	0.5	0.8	917.44	4.559	4.6	31.08	31.11	30.81	99.01
	710	0.25	1	721.62	4.451	4.477	30.25	30.28	30.08	99.32
	710	0.355	1.5	799.26	4.477	4.515	30.51	30.54	30.25	99.06
	710	0.5	0.5	944.7	4.521	4.559	30.81	30.83	30.55	99.08

	1120	0.25	0.75	1081.2	4.244	4.284	28.95	28.97	28.68	98.98
	1120	0.355	0.5	1314.07	4.32	4.344	29.35	29.37	29.19	99.38
	1120	0.5	1	1396.5	4.233	4.269	28.85	28.86	28.60	99.09
3	710	0.18	0.1	444.64	4.008	4.106	27.74	27.76	27.08	97.56
	710	0.2	0.5	996.8	3.969	4.008	27.08	27.13	26.82	98.84
	1120	0.18	0.5	1015.18	4.296	4.325	29.22	29.26	29.03	99.22
	1120	0.2	0.1	828.4	4.284	4.295	29.02	29.05	28.95	99.66

Conclusion

Thus exergy analysis is used in a turning process to determine the degree of perfection and thereby arrive at the optimal machining condition. This helps in improving the process and reducing cost without the need to invest on costly technologies.

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