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TRACES OF SIMILARITY AND CONSISTENCY OF DATA IN THE CHOICES OF SPECIFIC CUTTING ENERGY MODELS FOR PREDICTING CUTTING FORCE IN METAL CUTTING BY MACHINING PROCESSES

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Abstract

The specific cutting energy is of significant interest in predictive performance evaluation in metal cutting, as it aids in estimating the main cutting force. Several models and methods have been proposed for estimating the specific cutting energy, with some suggested models under-predicting, some over-predicting, for a given set of defined cutting conditions. This paper presents some applicable methods and reported supporting data for computational predictive evaluation during metal cutting, with validations on actual representative metal cutting data. Evidence shows that each proposed model can predict the main cutting force through simulated variation of the cutting conditions.

Keywords: *Specific Cutting Energy, Cutting Stiffness, Cutting Force, Specific Cutting Pressure.*

1. Introduction

The Specific Cutting Energy (SCE), U, depends on the hardness and undeformed or uncut chip thickness of the workpiece material and is defined as the energy required to remove a volume of workpiece material, and varies from one material to another [1]. The primary application predicts the main cutting force through the relation: $F_c = U.a_c.a_p$. Where 'a_c' and 'a_p' are the uncut chip thickness and depth-of-cut or back-engagement, respectively. Astakhov [2] gave a historical review of several old, to the modern state-of-the-art approaches suggested for estimating the specific cutting energy. Boothroyd [1]; Metcut Research [3]; Drozda, & Wick [4]; Shaw [5]; Kalpakjian, & Schmid [6]; Groover [7]; Velchev, Kolev, & Ivanov [8], [9] presented data and approximate methods based on experimental measurements conducted on various workpiece materials to aid estimation of the specific cutting energy, also termed, the Total Energy per unit volume or Specific Cutting Pressure. Some researchers, Black & Kohser [10], use Cutting Stiffness, particularly when analysing metal cutting vibrations.

Tabulated and graphical data for various workpiece materials suggested by different authors for SCE modelling are available in the literature. Comparatively, there is evidence that for a defined set of cutting conditions, some of the suggestions over-predict the main cutting force, resulting in significant deviations from reported representative cutting data. Workable approaches are discussed in the following sections, and a validation check is done on actual representative cutting data for machining AISI 4130 workpiece material using High Speed Steel (HSS) cutting tool.

2. Different Approaches to Estimating Specific Cutting Energy, U

2.1 SCE - Method 1 - by Data Provided by Singh [11] and Groover [7]

Table 1 data was developed from Singh [11] and Groover [7] and are usually applied with a Correction factor, Cf, due to what is termed the size effect, in form of eq. 1. The Size Effect" indicates the influence of increase or decrease in undeformed chip thickness on specific cutting energy, that is, as undeformed chip thickness is reduced, the specific cutting energy increases [7]. Thus, the specific cutting energy based on the correction for the size effect in using the Singh [11] and Groover [7] data is applied in the form:

$$U_{corrected} = C_f . U_{from\text{-}table} \qquad (1)$$

Groover [7] presented a graph of Correction factor versus uncut or undeformed chip thickness, which is obtained for the undeformed or uncut chip thickness or feed rate range for Orthogonal cutting: 0.036 mm $\le$ ac $\le$ 1.25 mm. Readings of the Groover influence the errors or uncertainties [7] graph, with extracts made from two

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**Corresponding Author - E- mail: tonyekjack@yahoo.com* readings within the ranges of: 1.8 ≤ Cf ≤ 0.63 and 1.75 ≤ Cf ≤ 0.58.

Jack [12] conducted detailed curve-fits and derived power-law correlations for the correction factor, Cf, as follows:

2.1.1 Correction Factor for Estimation of Specific Cutting Energy Based on Data by Groover [7]

The more accurate prediction in the derived curve-fit correlations by Jack [12] for the Correction factor is by the correlated eq. (2) with a deviation of 2.18 percent:

$$C_f = 0.68902.a_C^{-0.30663} \qquad (2)$$

The correlated eq. (3) also closely predicts with an overall deviation of 11.6 percent, but with errors at some extracted data points:

$$C_f = 0.65017.a_C^{-0.19556} \qquad (3)$$

Another correlation with the equation. (4a), with an overall deviation of 9.04 percent also, it also closely predicts higher values of the undeformed or uncut chip thickness:

$$C_f = 1.02254 \cdot e^{-0.47364 a_c} = 1.02254 \cdot \left[\exp\left(-0.47364 \cdot a_c\right)\right] \qquad (4a)$$

Yet another correction factor equation, at higher values of the undeformed or uncut chip thickness, also closely predicts in line with eq. (4b) with overall deviation of 8.84 – percent as follows,:

$$C_f = 1.40144 \cdot e^{-0.74263 a_c} = 1.40144 \cdot \left[\exp\left(-0.74263 \cdot a_c\right)\right] \qquad (4b)$$

Other variables such as rake angle, cutting speed, feed rate and cutting edge angle, and cutting fluid also affect the specific energy [7].

2.1.2 Effect of Rake Angle and Feed Rate in Specific Cutting Energy Estimation Based on Data by Shaw [5]

The effect of the undeformed chip thickness, rake angle, and cutting edge angle is captured by a relationship given by Shaw [5], for estimating specific cutting energy:

$$U = U_{table\text{-}data} \cdot \left(1 - \frac{\alpha_n - \alpha_e}{100}\right) \cdot \left(\frac{0.25}{f}\right)^{0.2} \qquad (5)$$

Where, αe, is the effective rake angle for the Orthogonal model, αe = 0, then eq. (5) becomes:

$$U = U_{table\text{-}data} \cdot \left(1 - \frac{\alpha_n - 0}{100}\right) \cdot \left(\frac{0.25}{f}\right)^{0.2} \qquad (6)$$

In this instance, the effective rake angle is set at “0” degrees.

Note that the Groover [7] basic data for specific cutting energy in Table 1 can be applied with the Shaw [5] eqs. (5) and (6) with success. The validations and verifications have been confirmed by Jack [12].

2.2 SCE - Method 2 - by Data Provided by Boothroyd [1]

Boothroyd [1] provided graphical data of specific cutting energy versus uncut chip thickness. Extracts from the graphical data are shown in Table 2. In order to arrive at a computationally applicable model for predicting the main cutting force, the extracts of Boothroyd [1] data in Table 2 were averaged with the data of Table 2a, and curve-fitted power-law equations of Specific Cutting Energy versus uncut chip thickness were derived by Jack [12] for different workpiece materials as follows:

Carbon Steels:

$$U = 1.8612.a_{c-avg}^{-0.4267} \qquad (7)$$

The error or uncertainty in prediction is 7.40percent.

Alloy and Stainless Steels:

$$U = 2.5305.a_{c-avg}^{-0.4196} \qquad (8)$$

The error or uncertainty in prediction is 4.11percent.

Gray, Ductile and Malleable Cast-Irons:

$$U = 1.158.a_{c-avg}^{-0.4571} \qquad (9)$$

The error or uncertainty in prediction is 5.40 percent.

Aluminium Alloys:

$$U = 0.4252.a_{c-avg}^{-0.5447} \qquad (10)$$

The error or uncertainty in prediction is 8.00 percent.

Copper Alloys, including Brass:

$$U = 0.631.a_{c-avg}^{-0.5462} \qquad (11)$$

The error or uncertainty in prediction is 7.30 percent.

Analytical evidence shows that the Boothroyd [1] data tended to overestimate the Specific Cutting Energy at a defined set of cutting conditions when compared to literature-reported experimental Specific Cutting Energy data values.

Table 1 Basic Approximate Specific Cutting Energy Data at various Brinell Hardness Numbers (BHN) (Groover [7] and Singh [11])

Work-piece Material Type	Brinell Hardness Number (BHN)	Basic Approximate Specific Cutting Energy (GJ/m^3)
Carbon Steel	85 -to- 150	1.4
	150 -to- 200	1.6
	200 -to- 250	2.2
	> 251	2.8
Alloy Steel	200 -to- 250	2.2
	251 -to- 300	2.8
	301 -to- 350	3.5
	351 -to- 400	4.2
Stainless Steel	135 -to- 275	1.4
	> 275	1.6
Cast-Iron	110 -to- 190	0.8
	190 -to- 320	1.6
Aluminium Alloy	30 -to- 150	0.35
Brass	≤ 147	0.8
	> 147	1.6

Table 2 Basic Approximate Specific Cutting Energy, U, Data (in GJ/m^3) at Various Undeformed or Uncut Chip Thicknesses. (Boothroyd [1])

Undeformed or Uncut Chip Thickness (mm)	Alloy Steels		Carbon Steels		Cast Irons		Copper Alloys		Aluminium Alloys	
	U Lower	U Higher	U Lower	U Higher	U Lower	U Higher	U Lower	U Higher	U Lower	U Higher
0.045	8	10	6	8	3.5	6	2.5	3.5	2	2.5
0.06	7	9	5.5	7	3.25	5.5	2	3.25	1.75	2
0.08	6.5	8.25	4.5	6.5	3	4.5	1.9	3	1.5	1.9
0.1	6	8	3.75	6	2.5	3.75	1.75	2.5	1.4	1.75
0.2	3.9	6	3.5	3.9	1.9	3.5	1	1.9	0.8	0.9
0.4	3.5	4	2.5	3.5	1.25	2.5	0.7	1	0.6	0.7
0.6	3	3.5	2	3.5	0.9	2	0.65	0.9	0.55	0.65
0.8	2.5	3.5	1.75	2.5	0.8	1.75	0.6	0.8	0.5	0.6
1	2	2.5	1.25	1.5	0.7	1.25	0.5	0.7	0.4	0.5

Table 2a Averaged Basic Approximate Specific Cutting Energy, U, Data (in GJ/m3) of Boothroyd [1] – at Various, Undeformed or Uncut Chip Thicknesses.

Undeformed or Uncut Chip Thickness (mm)	Alloy Steels	Carbon Steels	Cast Irons	Copper Alloys	Aluminium Alloys
	U Averaged	U Averaged	U Averaged	U Averaged	U Averaged
0.045	9	7	4.75	3	2.25
0.06	8	6.25	4.38	2.63	1.88
0.08	7.38	5.5	3.75	2.45	1.7
0.1	7	4.88	3.13	2.13	1.58
0.2	4.95	3.7	2.7	1.45	0.85
0.4	3.75	3	1.88	0.85	0.65
0.6	3.25	2.75	1.45	0.78	0.6
0.8	3	2.13	1.28	0.7	0.55
1	2.25	1.38	0.98	0.6	0.45

Note: A curve-fit of the averaged Boothroyd [1] Specific Cutting Energy, *U*, *versus* undeformed chip thickness, a_c, is as given by eqs. (7 -11).

Table 3 Basic Approximate Specific Cutting Energy Data of Shaw [5] at Undeformed or Uncut Chip Thickness, ac = 0.25 mm, and Effective Rake Angle, αe = 0 deg.

Work-piece Material Type	**Approximate Specific Cutting Energy** (GJ/m^3)	**Extended Approximate Application in this work**
Mild Steel, such as AISI 1018	2.106	AISI 1005 -to- AISI 1095
Stainless steel, such as AISI 304 and high-temperature alloys, such as Nickel and Cobalt	4.914	AISI 201 -to- AISI 446
Free machining steel such as AISI 1213	1.755	All Free-Machining Steels
Titanium Alloys	3.510	All Titanium Alloys
Aluminium Alloys	0.702	All Aluminium Alloys
Cast-Iron, such as Gray, Ductile and Malleable Cast-Irons	1.053	All Gray, Ductile and Malleable Cast-Irons
Brass such as Naval and admiralty brass	1.053	All Brass alloy materials
Addendum:		
Alloy Steel (data taken from Metcut [3])	2.123	AISI 2XXX -to-AISI 9XXX

Note: Shaw [5] Aluminium data compares to the suggested data by Metcut [3] for the feed rate range: 0.12 – 0.50 mm/rev

Table 4 Validation Checks for various approaches at Estimation of Specific Cutting Energy, U, based on the defined cutting conditions.

Experimental =		U = 2206 (GJ/m^3)		F_c=1690 (N)
Applied Method / SCE Model Data	**Applicable Equation**	**Computed *U* (GJ/m^3)**	**Absolute Error or Deviation (percent)**	**Estimated Main Cutting Force, F_c (N)**
Method 1 using Groover's basic data; $U_{table\text{-}data}$= 2.2 GJ/m^3	Equation (6)	2167	1.77	1678
Method 1 using Groover's basic data ($U_{table\text{-}data}$= 2.2 GJ/m^3)	Equation (1) with correction factor, C_f, equation (2)	3521	59.61	2727

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Method 2 using Boothroyd data	Eq. (8)	8019	263.51	6210
Method 3 using Shaw's basic data $U_{table\text{-}data}$= 2.123 GJ/m^3	Eq. (6)	2091	5.21	1619
Method 4 using Ernst & Merchant model	Eq. (12)	2213	0.32	1714
Method 4 using Zorev model (κ_r=45 deg.)	Eq. (13)	2066	6.34	1600
Method 4 using Rozenberg and Eremin model	Eq. (15)	1602	27.38	1240
Method 4 using Velchev model	Eq. (16)	2848	29.10	2205
Method 4 using Kronenberg model	Eq. (19)	1465	33.59	1134

Table 5 Comparative Validation Checks on Shaw Recommened Cutting Data and Effect of Choice of Shear Angle Theory (SAT) at Estimation of Specific Cutting Energy, U, on the reliability of Ernst and Merchant model.

Experimental =		U = 2206 (GJ/m^3)		F_c=1690 (N)
Applied Method SCE Model Data; Shear Angle Theory (SAT)	**Applicable Equation**	**Computed *U* (GJ/m^3)**	**Absolute Error or Deviation (percent)**	**Estimated Main Cutting Force, F_c (N)**
a.) using Ernst & Merchant model; Bastein & Weisz SAT : $\varphi_n = 54.7-\beta_n+\alpha_n)$	Equation (12)	2213	0.32	1714
b.) using Ernst & Merchant model; Merchant SAT : $\varphi_n = 45-½(\beta_n-\alpha_n)$	Equation (12)	2991	35.58	2316
c.) using Ernst & Merchant model; Krystof or Lee & Shaffer SAT: $\varphi_n = 45 - \beta_n+ \alpha_n$	Equation (12)	2066	6.35	1600

Table 6 Comparative Validation Checks on Effects of Choices and Differences in Specific Cutting Energy and Shear Angle Theory (SAT) in Prediction of Cutting Force through Simulated Variation of Cutting Conditions During High Speed (V = 600 m/min) Machining of Aluminium Alloy AL 6061-T6-T.

Parameter	**Experimental-from Marusich [17]: Read from graphs (Approximate, due to reading error)**	**Groover Data; Check *(i)* with (Krystof SAT) and Percent Error in Prediction**		**Shaw data; Check *(ii)* with (Krystof SAT) and Percent Error in Prediction**		**Boothroyd data; Check *(iii)* with (Krystof SAT) and Percent Error in Prediction**		**Groover data; Check *(iv)* with (Bastein & Weisz SAT) and Percent Error in Prediction**	
			Percent Error		**Percent Error**		**Percent Error**		**Percent Error**
Feed rate, f	0.075	0.075		0.075		0.075		0.075	
Rake Angle, α_n	10	10	0.00	**4**	60.00	**4**	60.00	10	0.00
F_c (N)	325	324.62	0.12	325.93	0.27	326.85	0.57	324.62	0.12
F_f (N)	125	120.43	3.66	125.72	0.58	126.08	0.86	187.83	50.26
Θ_{max} (Deg.C)	282	271.95	3.57	475.38	68.57	1019.54	261.54	293.40	4.04
Predicted a_p, (mm)	**N/A**	**10.80**		**5.45**		**2.50**		**10.80**	
Φ_n, (deg.)	21	24.65	17.38	23.91	13.86	23.91	13.86	24.65	17.38
β_n, (deg.)		30.35		25.09		25.09		40.05	
U (GJ/m3)		0.401		0.797		1.743		0.401	
τ_s (MPa)	112	126.04	12.54	244.90	118.66	535.39	378.03	111.57	0.38
Form factor (U/τ_s)		3.18		3.25		3.26		3.59	
Chip Thickness, t_c (mm)	0.174	0.174		0.174		0.174		0.174	
Predicted r_c	N/A	0.431		0.431		0.431		0.431	

2.3 SCE - Method 3 - by Data Provided by Shaw [5]

Shaw [5] presented the basic data shown in Table 3 for Specific Cutting Energy for selected American Iron and Steel Institute (AISI) designated steel workpiece materials. The data in Table 3 can be applied with the Shaw [5] relation of eqs. (5) and (6). Since workpiece materials suitable for any particular cutting application are available for various designated metals or steel materials, Jack [12] extended the basic Shaw [5] data of Table 3, by assuming material microstructure similarity in line with the AISI steel materials classification by Deutschman, Michels, and Wilson [13] through the following groupings as a function of maximum permissible percentage Carbon content:

i. Low Carbon steel: 0.05 -to- 0.25 – percent;
ii. Medium Carbon steel: 0.30 -to- 0.50 – percent;
iii. High Carbon steel: > 0.50 – percent.
    a. Thus, by the Deutschman, et al. [13] classifications, the literature reported AISI steels groupings as a function of maximum permissible percentage Carbon content are:
iv. Low Carbon Steel: AISI 1005 -to- AISI 1025;
v. Medium Carbon Steel: AISI 1026 -to- AISI 1055;
vi. High Carbon Steel: AISI 1056 -to- AISI 1095;
vii. Other steels of related interest in line with the Shaw [5], listing are:

viii. Free Cutting Steels are of the form : AISI 11XX, 12XX;
ix. Other Carbon Steels of the form: 13XX, 15XX;
x. Alloy Steels: AISI 23XX, AISI 31XX, AISI 4023 -to- AISI 9440;
xi. Stainless Steels: AISI 201 -to- AISI 446.

By following the groupings given, and understanding that the Specific Cutting Energy is related to the Hardness (i.e. the Brinell Hardness Numbers, BHN, in this instance) of the workpiece material, other workpiece materials not listed by Shaw [5] can be related to similar material in the AISI designated grouping through the ratios of BHN values, as suggested by Drozda and Wicks [4] to estimate the Specific Cutting Energy of the particular material by the basic Shaw [5] reference data.

For example, Shaw [5] listed the Specific Cutting Energy of AISI 1018. To obtain the Specific Cutting Energy of, say, AISI 1005, the listed AISI 1018 Specific Cutting Energy value is multiplied by the ratio (BHN of 1005/BHN of 1018). By that analogy, the Shaw [5] basic data are extended, in estimating the Specific Cutting Energy for other materials within similar AISI groupings. Applying the method enabled data column listings for Specific Cutting Energy in an integrated database developed by Jack [12] for 500 workpiece materials to aid metal cutting predictive analysis.

2.4 SCE – Method 4- Other Specific Cutting Energy Modelling Approaches

Other models for determining the Specific Cutting Energy with varying levels of accuracy have been reported by Velchev, Kolev and Ivanov [9] as follows:
Based on the work of H. Ernst and M. E. Merchant in 1941,

$$U = \frac{\tau_s.\cos(\beta_n - \alpha_n)}{\sin\phi_n.\cos(\phi_n + \beta_n - \alpha_n)} \tag{12}$$

Based on the work of Zorev in 1956,

$$U = \tau_s\left(\frac{1}{\tan\phi_n} + \tan\kappa_r\right) \tag{13}$$

The Zorev model appears to be only suitable for application to oblique cutting in which the cutting edge is not straight. However, the cutting-edge angle, κ_r, aids in the estimation of the thickness of cut material being removed (i.e. the uncut chip thickness) when measured in the direction of the primary motion (i.e. measured both normal to the cutting edge and normal to the resultant cutting direction [1].

Kuppuswamy [14] defined two orthogonal system types when the chip flow angle, $\eta_c = 0$ deg., as follows:
Type I: $\kappa_r = 0$ deg.; When, $F_n = F_f$
The resultant force is then:

$$R_F = \sqrt{(F_f)^2 + (F_c)^2} \tag{14}$$

Type II: $0 < \kappa_r < 90$ deg.;
When, $F_f = F_n.\sin\kappa_r$, and, $F_r = F_n.\cos\kappa_r$
The resultant force is then:

$$R_F = \sqrt{(F_f)^2 + (F_r)^2} \tag{14a}$$

$$R_F = \{(F_n)^2 [(\sin\kappa_r)^2 + (\cos\kappa_r)^2]\}^{0.5}$$
$$R_F = \{(F_n)^2 [(1)]\}^{0.5} = \{(F_n)^2 [(\tan 45)]\}^{0.5} = F_n \tag{13b}$$

Type II occurs when the chip flow direction is normal to the cutting edge. Thus, by the Type II system for orthogonal cutting, the cutting direction occurs at $\kappa_r =$ 45 deg., which unarguably is in line with Altintas' [15] description of the Krystof maximum shear stress principle, and the Lee and Shaffer slip-line field shear angle theories in predicting the angle between the shear velocity and resultant force (i.e. the direction of the maximum shear stress or primary motion in orthogonal cutting as earlier stated by Boothroyd [1].

Based on the work of Rozenberg and A. N. Eremin in 1956,

$$U = 0.185.HV.\frac{\gamma}{1 - \sin\beta_n / [r_{cr}.\cos(\beta_n - \alpha_n)]} \tag{15}$$

Velchev, Kolev and Ivanov [8] also reported a set of equations for estimating U as a function of cutting velocity for steel, bronze and aluminium alloys, these are:
For Steel:

$$U = 2167 + \left(\frac{29550}{V + 16.4}\right) \tag{16}$$

For Bronze:

$$U = 1322 + \left(\frac{17120}{V + 10.32}\right) \tag{17}$$

For Aluminium Alloy:

$$U = 845 + \left(\frac{62730}{V + 156.2}\right) \tag{18}$$

And, yet another approach to estimating the energy consumption rate in metal cutting relates to the dependence of the Specific Cutting Energy on workpiece material hardness and the geometry of the tool rake angle in the cutting operation. Drozda and Wicks [4] reported details of an approximate relation due to Kronenberg as follows:
For Steels:

$$U = 4.26.\sqrt{BHN.(85-\alpha_n)} \qquad (19)$$

For Cast Irons:

$$U = 1.07.\left(\sqrt[2.5]{BHN}\right).\left(\sqrt{85-\alpha_n}\right) \qquad (20)$$

2.5 SCE - Specific Cutting Energy modelling data for Plastics/Polymers

The Specific Cutting Energy data for Carbon Fibre Reinforced Plastics/Polymers (CFRP) reported by Azmi, Syahmi, Naquib, Lih, Mansor and Khalil [16] is taken as representative for plastics and polymer materials, even though CFRP has a higher tensile strength than ordinary plastics and polymer materials. The applicable equation is:

$$0.1744a_c^{-0.717} \qquad (21)$$

3. Validation of Specific Cutting Energy Estimation Approach

Shaw [5] reported recommended metal cutting data for machining AISI 4130 steel (taken as Cold Drawn and Annealed – CDA steel). This is applied for validation of the various data and methods for estimation of the specific cutting energy and hence, the main cutting force. Bastein and Weisz shear angle theory is applicable (.i.e., $\varphi_n = 54.7 - \beta_n + \alpha_n$).

Workpiece Material = AISI 4130; Brinnel Hardness Number (BHN) = 201;

$a_c = f = 0.064$ mm; $a_p = 12.1$ mm; V = 27 m/min; $\alpha_n = 25$ deg.; $\varphi_n = 20.9$ deg.; $\beta_n = 58.8$ deg.; $\gamma = 2.55$; $r_c = 0.358$; τ_s=571 MPa.

Results of the validation exercise are shown in Table 4.

4. Conclusions

The validation and verifications checks in Table 4 at estimating for the energy required to remove a volume of workpiece material in machining AISI 4130 cold drawn and annealed steel using the various methods reported in this article shows that the data provided by Groover [7], Shaw [5], Ernst and Merchant equation (12), and Zorev equation (13) with deviations from the experimental of 1.77-percent, 5.21-percent, 0.32-percent, and 6.34-percent respectively, closely predict the specific cutting energy, and by extension the main cutting force with minimal uncertainty.

However, even though the Ernst and Merchant eq. (12) gives the least error, the noted challenge posed is in predicting the shear yield stress, τ_s, on the shear plane, and the selection of an appropriate shear angle theory, since certain theories for shear angle may suitably fit with machining some workpiece materials and fail for some other materials. Table 5 shows a comparative validation check on the reliability of the Ernst and Merchant equation using different shear angle theories, showing that the Krystoff (or Lee & Shaffer) model also gives good predictions with minimal error.

Jack (12) developed a computer program for the predictive performance evaluation of metal cutting by lathe machining processes. Using the program, evidence shows that for a fixed feedrate, *f*, specific cutting energy is greatly influenced by depth of cut, and/or rake angle, as shown by the simulated variation of cutting conditions of depth of cut, a_p, and/or rake angle, α_n, in the *high speed machining* of Aluminium Alloy, AL-6061-T6-T based on the validation checks conducted in this work whilst applying different specific cutting energy models and shear angle theories to Marusich (17) reported data in Table 6; the consequent effect on the prediction of the tool temperature, θ_{max}, should be noted in Table 6 results. Also of interest in Table 6 results is the near similarity of the form factor (U/τ_s); it is not clear why, but a possible reason can be adduced here that all specific cutting energy models can validly be applied for predicting a cutting operation, but with varied cutting conditions. From verification tests of several shear angle theories in this study, the fitting shear angle model for the Shaw [5] recommended cutting data for the AISI 4130 material was the Bastein and Weisz model.

5. Conflicts of Interest

There are no conflicts of interest in this publication.

6. Nomenclature

Symbol	Meaning	Unit
a_c	Uncut chip thickness	mm
$a_{c\text{-}avg}$	Averaged Uncut Thickness	mm
a_p	Depth of cut or Back-engagement	mm
C_f	Correction factor	-
f	Feed rate	mm/rev
F_c	Main Cutting Force	N
F_f	Feed Force	N
F_n	Norrnal Foce	N
F_r	Radial Force	N
HV	Vickers Hardness	
r_c	Chip Thickness Ratio	-
N/A	Not available	
r_{cr}	Chip Compression Ratio	-
R_F	Resultant Force	N
SAT	Shear Angle Theory	

t_c	Chip Thickness	mm
U	Specific Cutting Energy	GJ/m^3
V	Cutting Velocity	m/min
α_n	Rake Angle	deg.
β_n	Friction Angle	deg.
η_c	chip flow angle	deg.
φ_n	Shear Angle	deg.
Θ_{max}	Tool Temperature	Deg.C
γ	Strain	-
κ_r	Cutting-edge Angle	deg.
τ_s	Shear Yield Stress	MPa

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