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Impact of un-deformed chip thickness on specific energy in mechanical machining processes

Vincent A. Balogun
Paul T. Mativenga

Presenter: Dr. Vincent Aizebeoje Balogun
Department of Mechanical Engineering,
Edo University Iyamho, Edo State.

Research Outline

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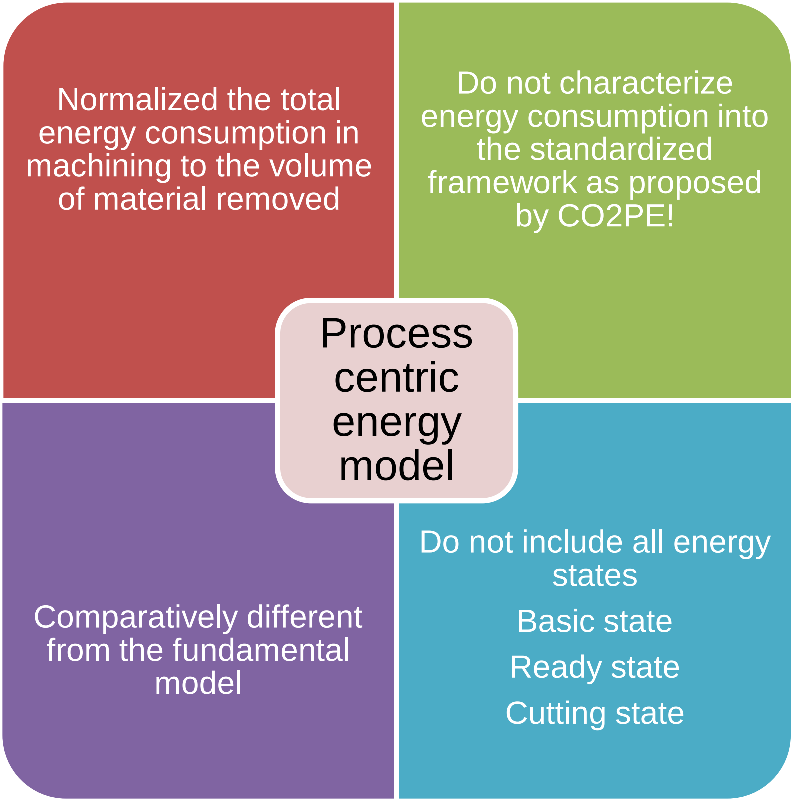
Research context

- Reducing electricity consumption and CO_2 emission is the driving force for optimizing energy demand.
- The fundamental approach to modeling energy in manufacturing processes and **Cooperative Effort on Process Emissions in Manufacturing** **(CO2PE!)** approach:
  - ❖ Basic energy state [1-2]
  - ❖ Tip energy state
  - ❖ Ready energy state [3]
- Fundamental model proposed by Gutowski et. al., [2]

$$E = \left(P_o + k\dot{v}\right)t$$

Research background

Current research approaches:



Normalized the total energy consumption in machining to the volume of material removed

Do not characterize energy consumption into the standardized framework as proposed by CO2PE!

Process centric energy model

Comparatively different from the fundamental model

Do not include all energy states

Basic state

Ready state

Cutting state

Authors	Specific energy model
Draganescu et al., (2003)	$Ecs = \frac{P_c}{60\eta Z}$ (2)
Li and Kara (2011)	$SEC = C_0 + \frac{C_1}{MRR}$ (3)
Diaz et.al., (2011)	$e_{cut} = k * \frac{1}{MRR} + b$ (4)
Where Ecs, SEC, e_{cut} represents specific energy consumption, P_c is the cutting power, η is machine tool efficiency, z and MRR represents the material removal rate, C_0 and C_1 are empirical coefficients, k is a constant and has units of power and b represents the steady-state specific energy.	

Research background

Size effect in machining

- Chip formation in machining depends on
    - Material characteristic, cutting tool geometry, ratio of the feed per tooth to the cutting edge radius and minimum chip thickness
- The minimum chip thickness reported ranges of ratio of un-deformed chip thickness to cutting edge radius of 0.2 to 0.4
- No chip formed if ratio > 0.25.

Research progress on specific cutting pressure to date.

Author(s)	**Specific cutting pressure model**
Tayloy Kronenberg (1927).	$K_s = Ct^{-a}s^{-h}$ **(6)**
Pohl Schroder (1934).	$K_s = \alpha + \beta h^{-1}$ **(7)**
Kienzle, (1952).	$K_s = Ks_{1.1}h^{-x}$ **(8)**
Hippler HucKs (1955).	$K_s = C_1 q^{-0.25}$ **(9)**
Richter Hucks, (1955).	$K_s = A\left(1 + Bh^{-1}\right)$ **(10)**
Sabberwal, A. J. P., (1962).	$K' = C\left(t_c\right)^p$ **(11)**
Where *K*	

Where K_S and *K'* represent the specific cutting pressure, *C*, C_1, *α* and β are constants depending upon the workpiece material and cutting tool geometry, *t*, is the depth of cut, *h* is the chip thickness at any instant, *s* is the feed per tooth and *q* is the area at any instant.

Aim and objectives

- To evaluate the impact of the un-deformed chip thickness on specific cutting energy in mechanical machining processes.
- Investigate the specific electrical energy trends in machining with defined cutting edges focusing on the tool tip energy.
- Contribute towards the development of a realistic and robust model for estimating the specific cutting energy coefficient
- Define energy demand sustainability index of workpiece materials in mechanical machining
- Provide valuable data for resource efficient machining for energy centric production planning

Research methods

Cutting Experiment

Varying Cutting Parameters

Materials Characteristics (AW6082-T6 alloy, AISI 1045 steel alloy, and titanium 6Al-4V alloy)

Machine Tool

Power Measurement

Experimental details

Cutting parameters for milling trials

	Aluminium AW6082-T6 Alloy	AISI 1045 steel alloy	Titanium 6Al-4V alloy
Feed (mm/tooth)	0.01 – 0.55	0.01 – 0.55	0.01 – 0.55
Depth of cut (mm)	3.5	3.5	3.5
Cutting velocity (m/min)	210	156	80
Radial width of cut (mm)	0.25 – 1.00	0.25 – 1.00	0.25 – 1.00
Tool diameter (mm)	8	8	8
Chemical composition (Max)	1%Mn, 0.5%Fe, 1.2%Mg, 1.3%Si, 0.1%Cu, 0.2%Zn, 0.1%Ti, 0.25%Cr, Balance Al.	0.46%C, 0.40%Si, 0.65%Mn, 0.40%Cr, 0.10 Mo, 0.40%Ni, 0.63% Others	89.37%Ti, 6%Al, 4%V, 0.08%C, 0.3%Fe, 0.2%O2, 0.05%N
Material Hardness	HV 104.5	HV 238.2	HV 353.2

$$h_{avg} = \frac{f_z}{\varphi_s} \int_{0}^{\varphi_s} \sin\phi \, d\phi$$

Cutting tool geometry

Geometry	Values
Nose radius (mm)	0.4
Edge radius (µm)	60
Positive rake angle (deg.)	5
Rake face primary chip breaker land (µm)	60
Clearance angle (deg.)	7

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Taguchi analysis of cutting parameter variations

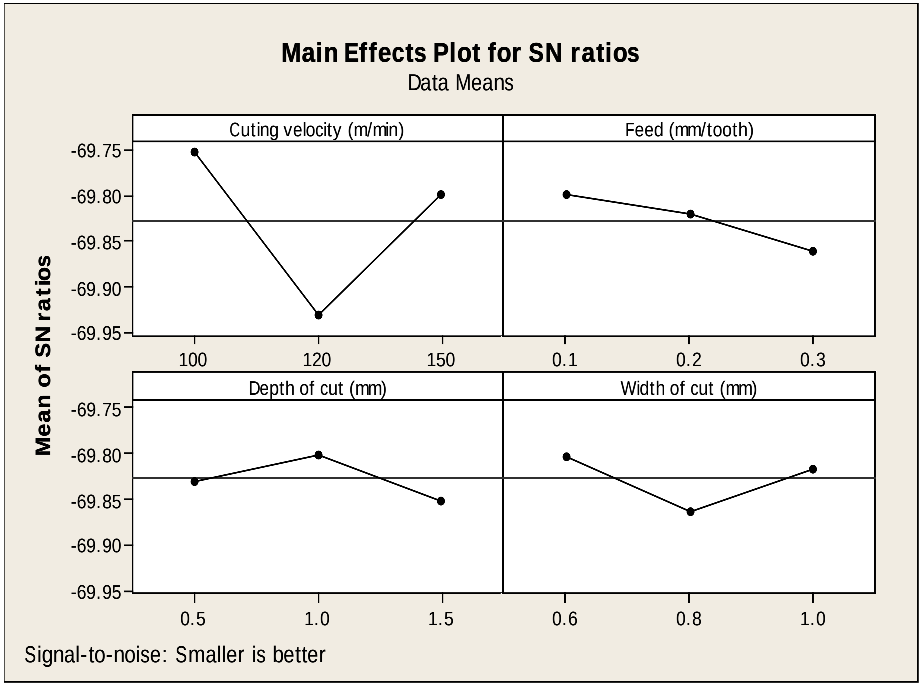
Taguchi L9 Responses

Cutting Velocity, v_c (m/min)	Feed per tooth, f_z (mm/tooth)	Depth of Cut, a_p (mm)	Width of Cut, a_e (mm)	Material Removal Rate, Q (mm^3/s)	Power (W)
100	0.1	0.5	0.6	1.33	3054.90
100	0.2	1.0	0.8	7.07	3074.07
100	0.3	1.5	1.0	19.89	3090.13
120	0.1	1.0	1.0	5.30	3113.68
120	0.2	1.5	0.6	9.55	3135.28
120	0.3	0.5	0.8	6.37	3164.69
150	0.1	1.5	0.8	7.96	3101.11
150	0.2	0.5	1.0	6.63	3084.31
150	0.3	1.0	0.6	11.94	3083.66

Width of cut = varied
Other parameters = constant

Process parameter ranking

Key Process variable ranking for power demand in machining of AISI 1045 steel alloy

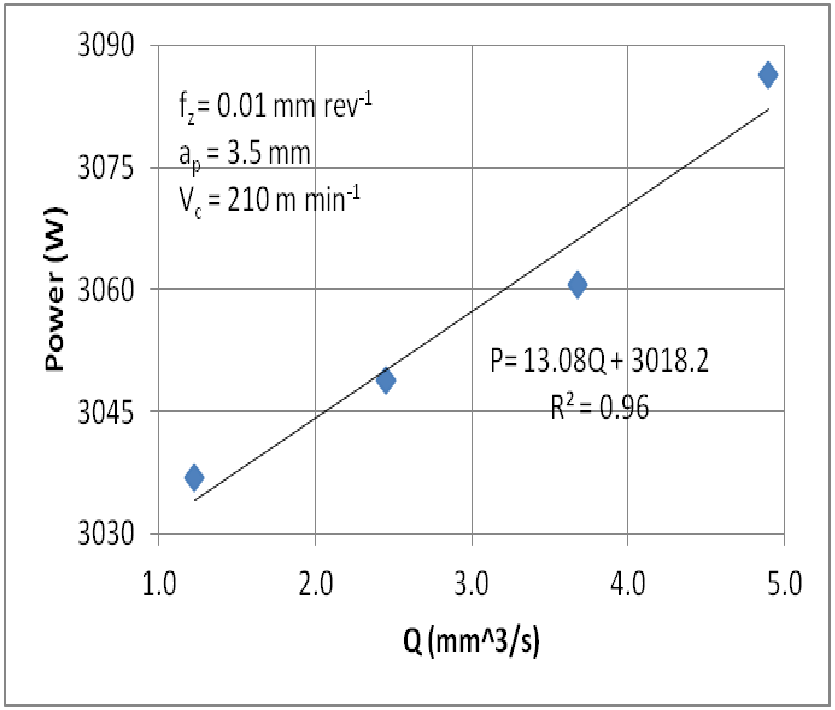


Level	v_c (m/min)	f_z (mm/tooth)	a_p (mm)	a_e (mm)
1	3073	3090	3101	3091
2	3138	3098	3090	3113
3	3090	3113	3109	3096
Delta	65	23	18	22
Rank	1	2	4	3

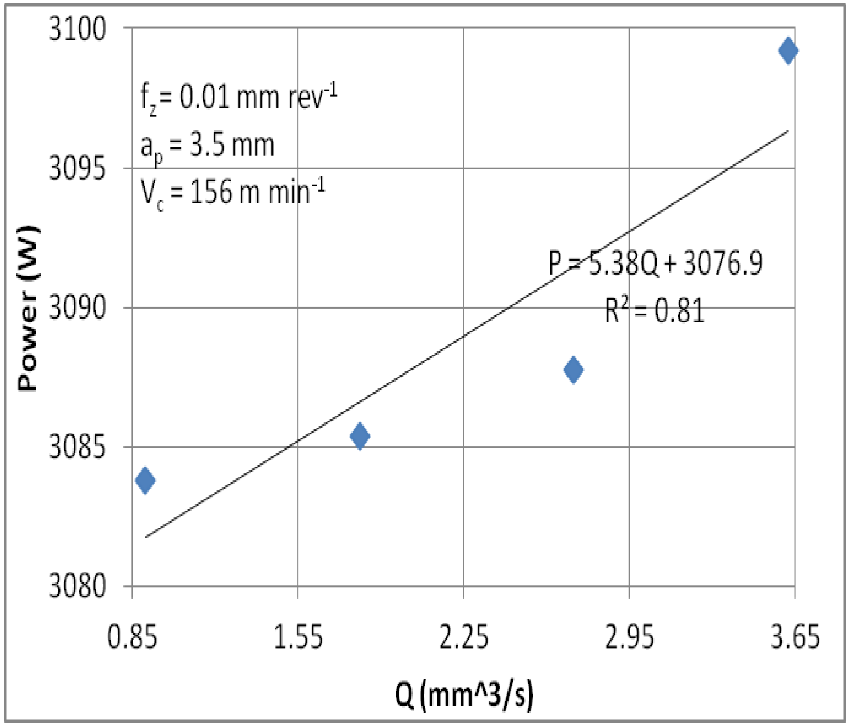
Results and Discussions

Evaluation of specific cutting energy coefficient at 0.01 mm/tooth

Aluminium AW6082-T6 alloy



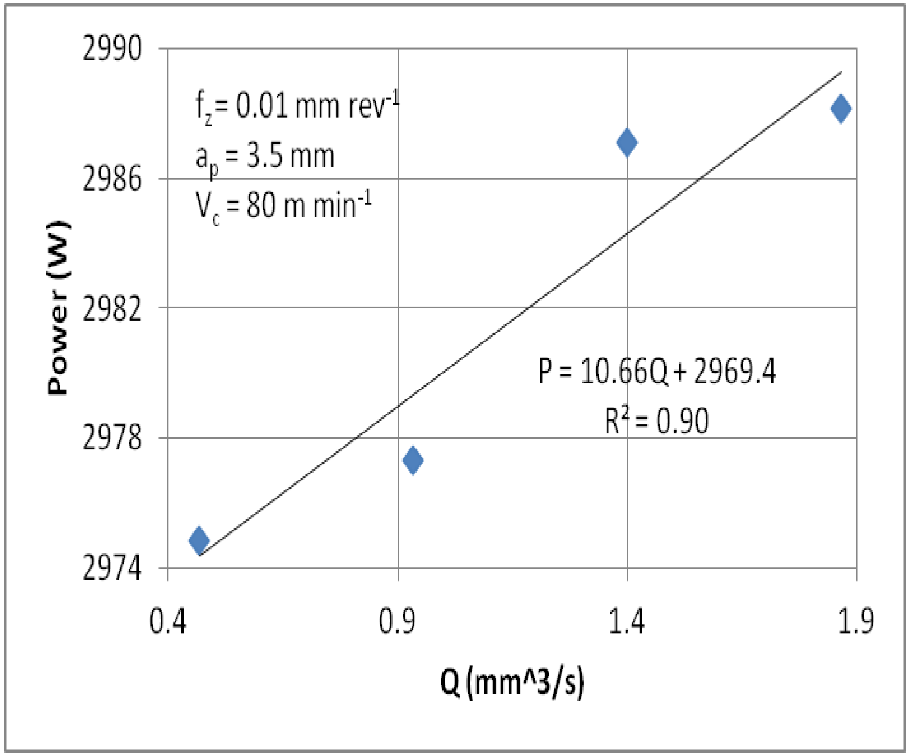
AISI 1045 steel alloy



Results and Discussions

Evaluation of specific cutting energy coefficient at 0.01 mm/tooth

Titanium 6Al-4V alloy



Specific Energy Coefficients (Ws/mm^3):

AISI 1045 steel alloy = 5.38

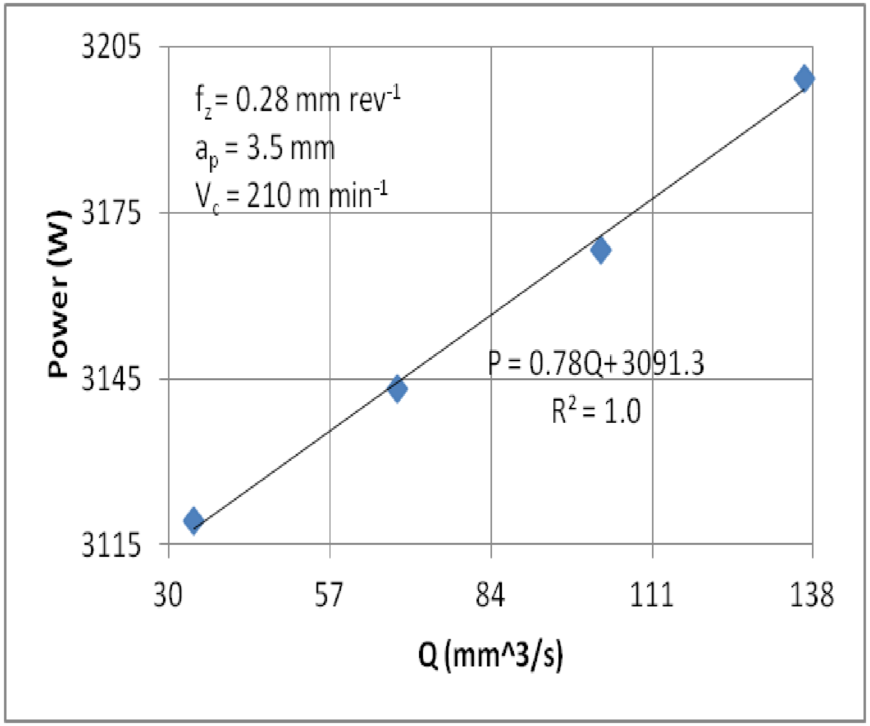
Titanium 6Al-4V alloy = 10.66

Aluminium AW6082-T6 alloy = 13.08

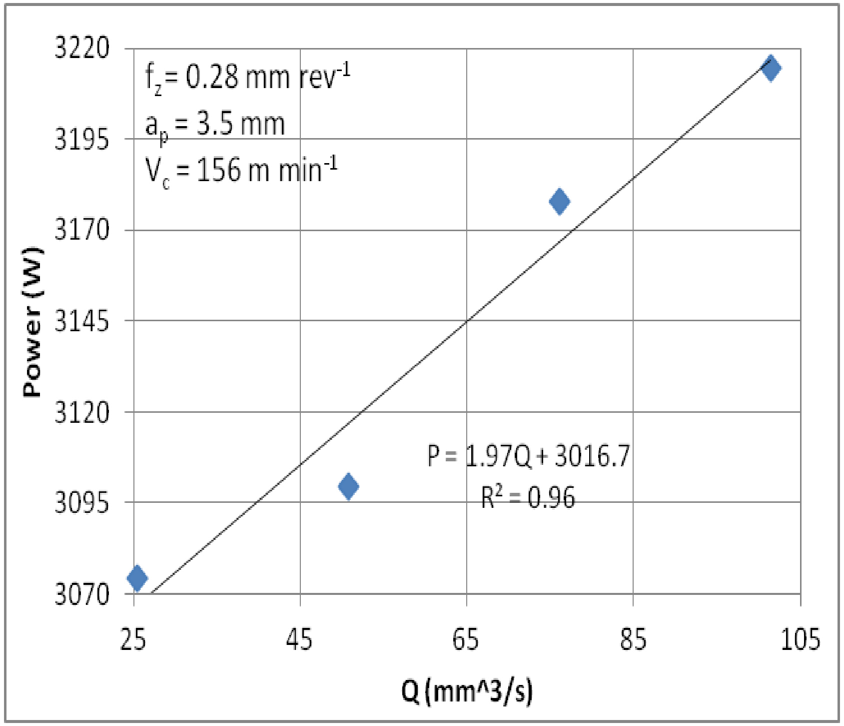
Results and Discussions

Evaluation of specific cutting energy coefficient at 0.28 mm/tooth

Aluminium AW6082-T6 alloy



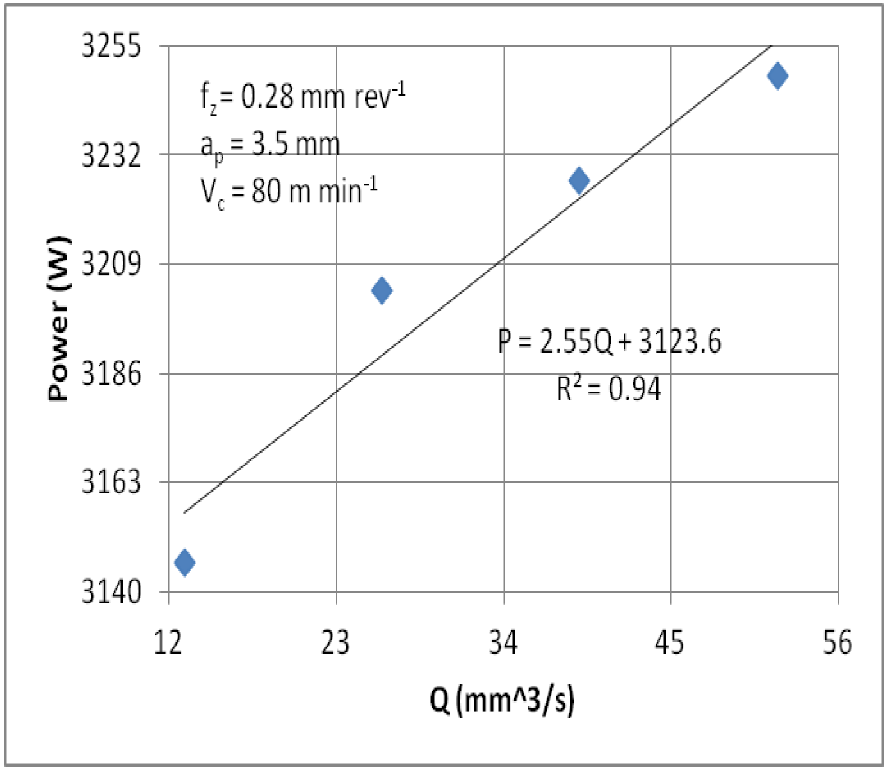
AISI 1045 steel alloy



Results and Discussions

Evaluation of specific cutting energy coefficient at 0.28 mm/tooth

Titanium 6Al-4V alloy



Specific Energy Coefficients (Ws/mm^3):

AISI 1045 steel alloy = 1.97

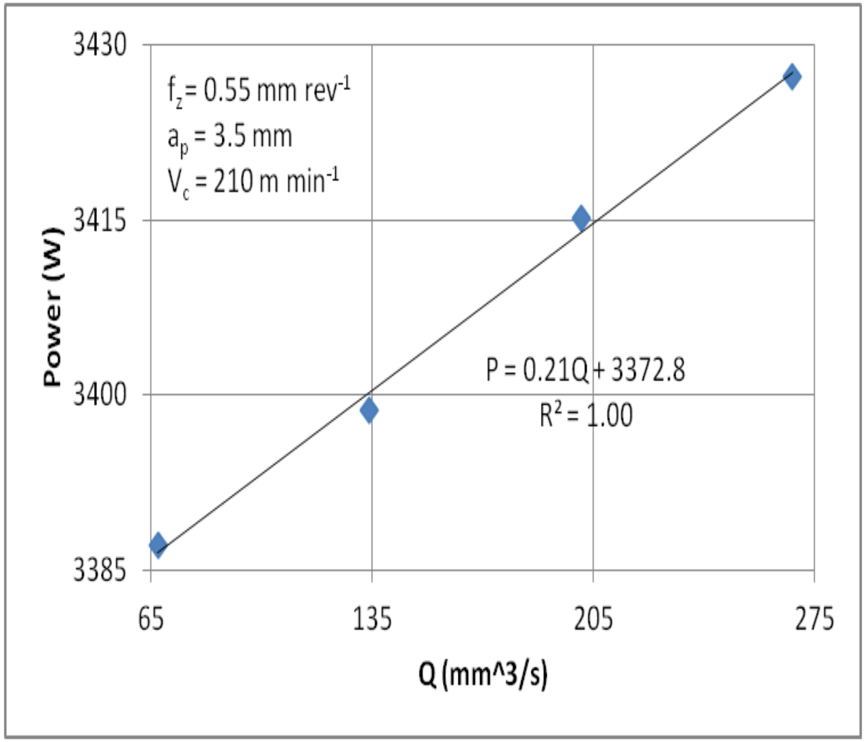
Titanium 6Al-4V alloy = 2.55

Aluminium AW6082-T6 alloy = 0.78

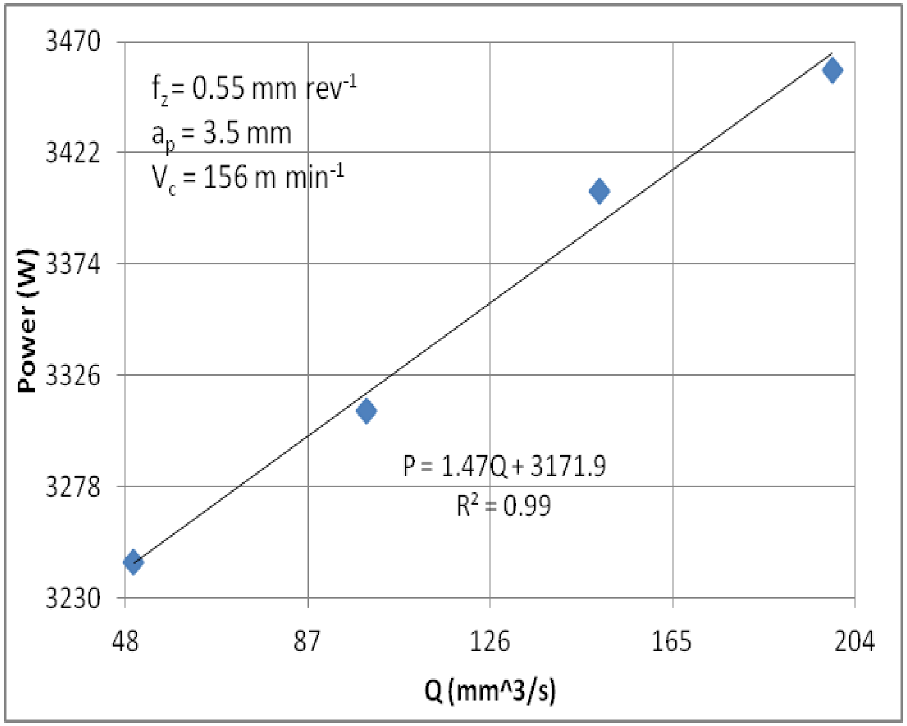
Results and Discussions

Evaluation of specific cutting energy coefficient at 0.55 mm/tooth

Aluminium AW6082-T6 alloy



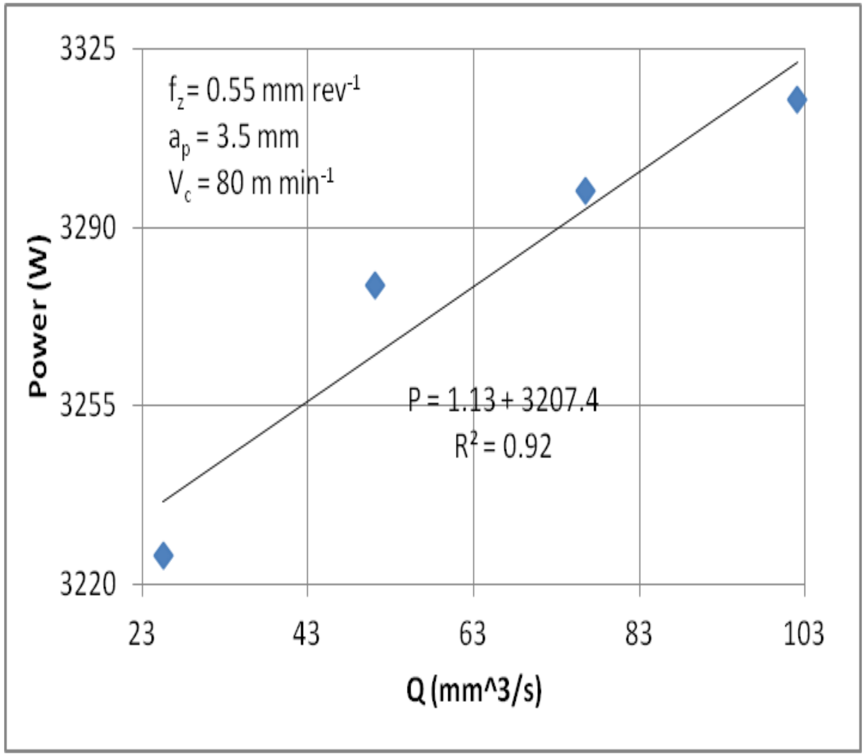
AISI 1045 steel alloy



Results and Discussions

Evaluation of specific cutting energy coefficient at 0.55 mm/tooth

Titanium 6Al-4V alloy



Specific Energy Coefficients (Ws/mm^3):

AISI 1045 steel alloy = 1.47

Titanium 6Al-4V alloy = 1.13

Aluminium AW6082-T6 alloy = 0.21

Results and Discussions

		Data obtained in this study							Literature values
	fz (mm/tooth)	0.01	0.10	0.19	0.28	0.37	0.46	0.55	
	h_{avg} (µm)	3	35	66	97	128	159	190	**Kalpakjian** 2004
Specific cutting energy (Ws mm^{-3})	Aluminium AW6082-T6 Alloy	13.08	1.99	1.52	0.78	0.87	0.21	0.21	0.40- 1.00
	AISI 1045 steel alloy	5.38	3.73	2.08	1.97	1.65	1.55	1.47	2.00- 9.00
	Titanium alloy	10.66	4.45	3.78	2.55	2.65	1.14	1.13	2.00- 5.00

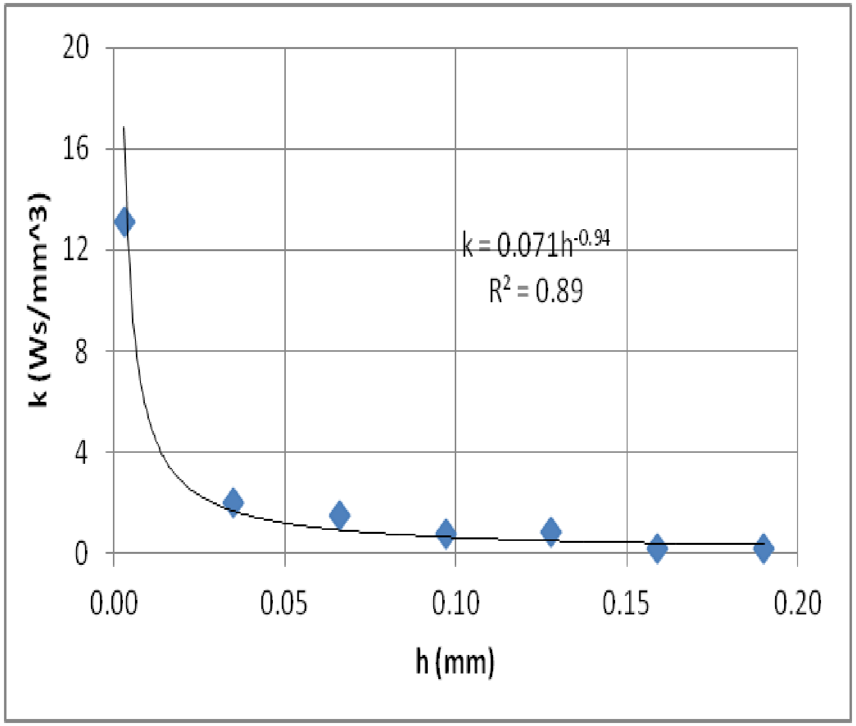
Process window

$$h_{avg} = \frac{f_z}{\varphi_s} \int_0^{\varphi_s} \sin \phi \, d\phi$$

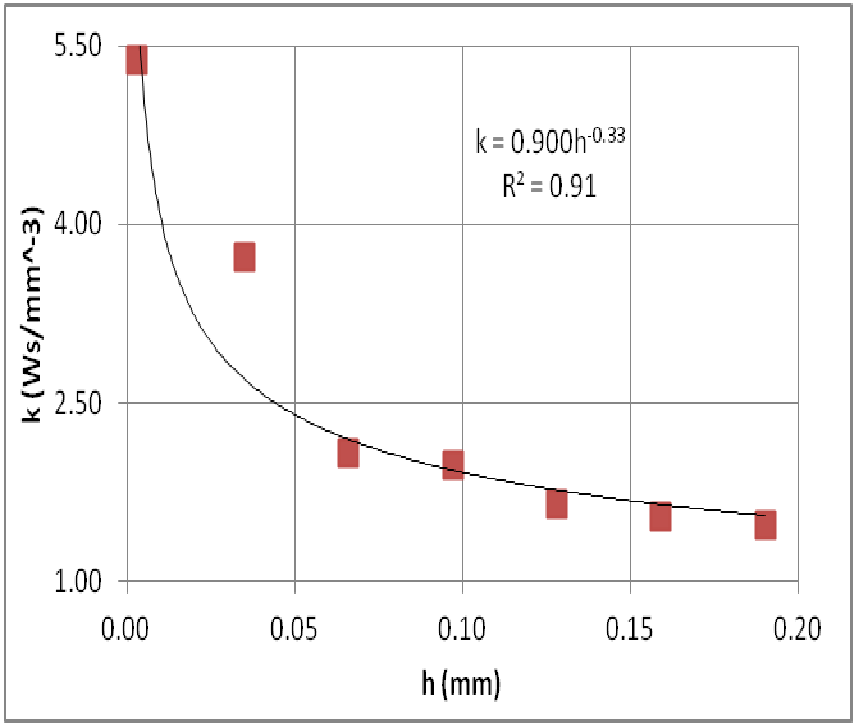
Results and Discussions

Specific cutting energy model

Aluminium AW6082-T6 alloy



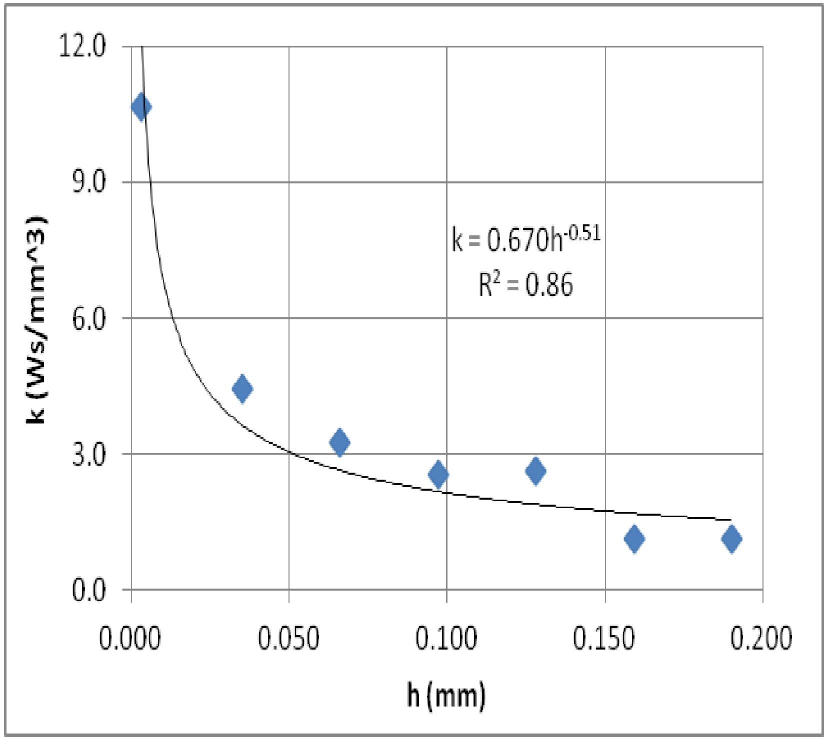
AISI 1045 steel alloy



Results and Discussions

Specific cutting energy model

Titanium 6Al-4V alloy



Developed models:

Aluminium alloy

$$k_{Al} = 0.071 * h^{-0.94}$$

AISI 1045 alloy

$$k_S = 0.900 * h^{-0.33}$$

Titanium alloy

$$k_{Ti} = 0.670 * h^{-0.51}$$

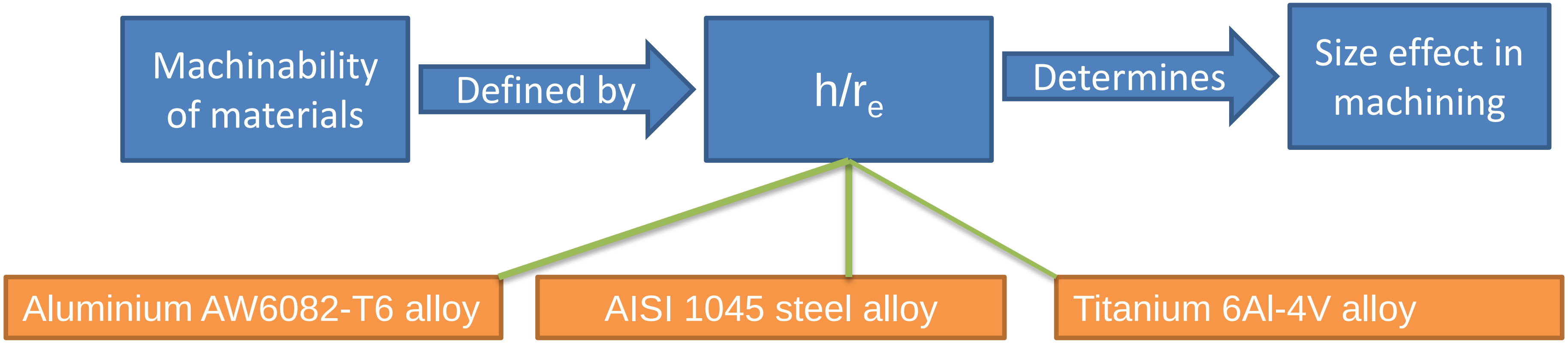
Generic model

$$k_e = K_e h^{-x}$$

Where k_{Al}, k_S, k_{Ti} and k_e represents the specific cutting energy in *Wsmm^{-3}*, *h* is the un-deformed chip thickness in *mm* and *x* is the specific energy exponent.

Specific energy and size effect

Energy efficiency for material removal



Machinability of materials

Defined by

h/r_e

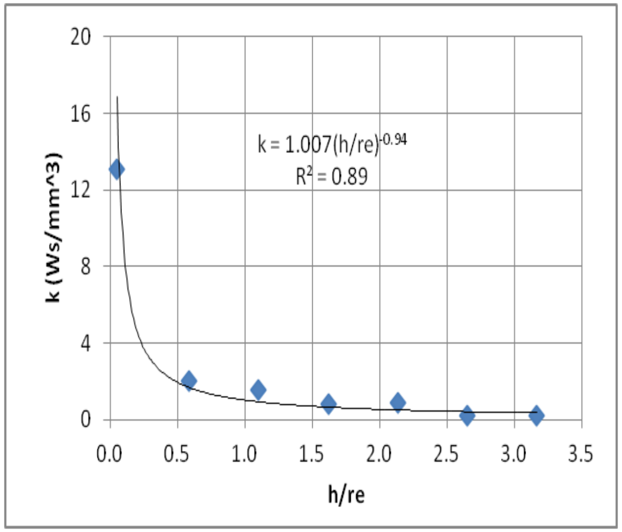
Determines

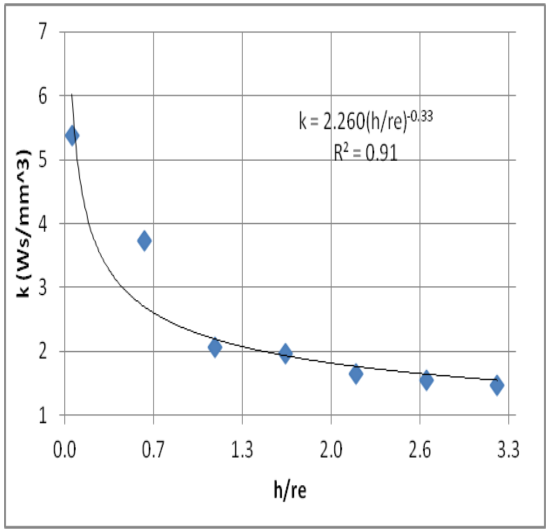
Size effect in machining

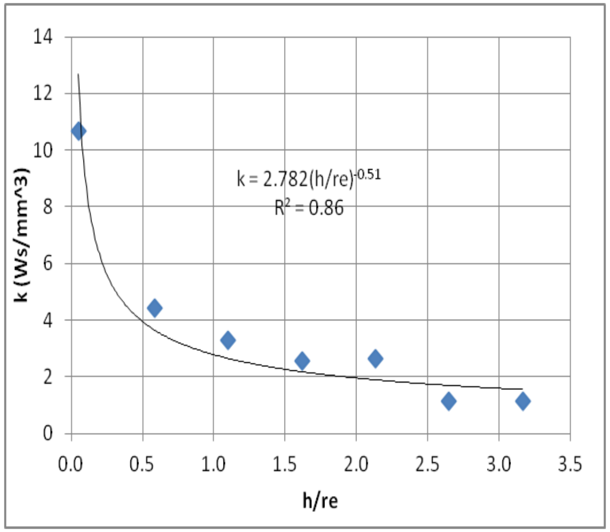
Aluminium AW6082-T6 alloy

AISI 1045 steel alloy

Titanium 6Al-4V alloy







Conclusions

Investigated the variation of specific energy coefficient for a wide range of un-deformed chip thicknesses and three different workpiece materials

The variation of specific energy with un-deformed chip thickness for three workpiece materials follows similar power function trends.

The specific energy for cutting aluminium alloys can be significantly high at very low un-deformed chip thickness to significantly low at chip thicknesses typical of conventional machining.

The average specific energy in conventional machining for a positive 5 degree rake angle carbide tools is 1.007, 2.260 and 2.782 $Wsmm^{-3}$ for aluminium AW6082-T6 alloy, AISI 1045 steel alloy and titanium alloy respectively.

Specific energy generic relationship

$$k_e = K_e h^{-x}$$

References

1. Dahmus, J., Gutowski, T., An environmental analysis of machining, in: ASME International Mechanical Engineering Congress (IMECE) and R&D Expo., Anaheim, California, 2004, pp. 1-10.
2. Gutowski, T., Dahmus, J., Thiriez, A., Electrical energy requirements for manufacturing processes, in: 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 2006.
3. Balogun, V.A., Mativenga, P.T., Modelling of direct energy requirements in mechanical machining processes, Journal of Cleaner Production, 41 (2013) 179-186.

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Thank you!