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# Optimum Swept Angle Estimation based on the Specific Cutting Energy in Milling AISI 1045 Steel Alloy

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*ABSTRACT*

Mechanical machining processes are common manufacturing strategies to re-shape materials to desired specification. The mechanistic approach has revealed the mechanics of the machining processes with various parameters determined. The aim of this work is to investigate the impact of swept angle optimization and their influence on the specific cutting energy in milling AISI 1045 steel alloy. This is achieved by varying the step over at different feed rate values in order to determine the optimization criterion for machining. It was observed that an optimum swept angle of 31.8$^{o}$ was appropriate in the elimination of ploughing effect and reducing the specific cutting energy to an optimised minimum value. However, higher swept angle of 41.4$^{o}$ increases the specific cutting energy with a higher machine tool power. This is attributable to the reduction in the cycle time caused by shorter toolpath length. The results obtained further elucidate the knowledge base for the determinations of optimum parameters for sustainable machining and resource efficiency of manufactured products.

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## 1. INTRODUCTION

Higher cost of consumer goods and services have been attributed to higher electrical energy consumption, cost due to value adding improvement of manufactured components, and advancement in manufacturing technology and facilities available [1]. This improvement for example is the additions of more auxiliary units to previously known mechanically manual and semi-automatic machine tools to perform functions that are more or less time consuming. These are done in order to improve their functionality and efficiency thereby increasing time-to-market product deliveries [2]. This functionality helps to improve product quality and reduce production time by optimising cutting parameters and electrical energy resource.

Increase in machine tools efficiency due to the addition of auxiliary units will obviously increase the electrical energy resource as each of this unit requires electrical energy to function effectively [3]. A trade-off is found to exist between the production time and cost, and product quality and energy resource. The need to reduce the electrical energy resource for manufacturing sustainability was emphasised when the International Standard Organisation ISO 14000 [4] agreed on the energy labelling of goods and services. This however, puts more pressure on manufacturers to provide goods and services that are environmentally friendly and resource efficient.

In mechanical machining, few important energy consumption parameters are well documented [5-8]. For example, tool life, workpiece materials, cutting parameters, machine tool characteristics, process variables, etc are key performance indicators that govern the surface integrity and aesthetics of finished consumer products. Although, the swept angle is one of the governing parameters that determines the tool life and tool wear characteristics, its importance has not been well investigated and documented in literature.

### 1. 1. Swept Angle and Tool Life Characteristics

It has been reported that machine tool contributes over

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70% towards the total energy resource of manufactured products [5-8]. The tool life is one of the major factors in machining theory that must be given due consideration in order to achieve better surface integrity [9, 10], lower machining and tool changing cost, and economic cost of manufacture for resource efficiency [11, 12].

The swept angle or the engagement angle has been identified as one of the selection criterion for tool life for minimum cost $t_c$, tool life for minimum production time $t_p$, and tool life for maximum efficiency $t_{ef}$ [13]. Bootroyd and Knight [13] in their analysis as modelled in Equations 1 and 1a, reported that in order to estimate the cutting speeds $v_{c,p,ef}$ which resulted in the values of the tool life for cost, minimum production and maximum efficiency, it is important to include the volume of material removed $Q$ for the proportion of machining time per component $t_c$. Hence,

$$v_{c,p,ef} = v_r \left(\frac{t_r}{Qt_{c,p,ef}}\right)^n \tag{1}$$

where for slab and face milling as in Figure 1;

$$Q = \frac{\emptyset}{2\pi} = \frac{1}{4} + \frac{1}{2\pi}\sin^{-1}\left(\frac{2a_e}{d_t} - 1\right) \tag{1a}$$

The undeformed chip thickness and the swept angle can be estimated with Equations 2 and 3, respectively adapted from [13] and shown below;

$$h_{m(avg)} = \frac{f_z}{\emptyset_s}\int_0^{\emptyset} Sin\emptyset \, d\emptyset \tag{2}$$

$$\emptyset_s = \cos^{-1}\frac{r - a_e}{r} \tag{3}$$

where, $n$ is the process parameter coefficient, $v_r$ is the cutting speed in *m/s* for a particular tool life $t_r$, $\emptyset$ is the cutter swept angle in degrees, $\emptyset_s$ is the cutter swept angle in radians, $a_e$ is the radial depth of cut or step over and $d_t$ is the cutter diameter in *mm* as shown in Figure 1.

From the analysis and Figure 1, a higher radial depth of cut $a_e$ increases the volume of material removed and vice versa.

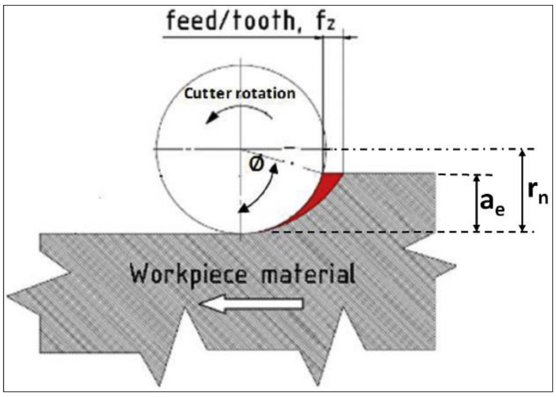


**Figure 1.** Cutter engagement with workpiece adapted from [14]

However, at a lower radial depth of cut, the tendency of a plastic deformation of the tool due to ploughing effect is very high as the total feed $f_z$ will not be the same at both entry and exit of the tool [15, 16]. Therefore, the chip thickness will be lower compared to the feed or chip load. In order to improve the machined surface integrity and reduce burr formation for resource efficient machining and sustainable manufacture, the swept angle is a required consideration.

## 1. 2. Relationship between Toolpath and Step Over

It has been reported, that during an end milling operation, the chip thickness is not too low when compared to the cutting edge radius [14, 17]. This is due to the fact that the chip thickness is affected by the radial depth of cut. The chip thickness decreases with the radial depth of cut unless the table feed (*feed/tooth*) is increased. If the radial depth of cut is less than half of the end mill diameter, the feed per tooth $f_z$ should be increased in order to increase the chip thickness. Tsai et al. [18] modified the toolpath in order to keep the swept angle constant, thereby keeping the cutting force and torque, constant. Although the author's technique is good, it may be difficult to see how this strategy can be applied to machining of complex geometries and toolpaths. Tarng and Shyur [19] investigated the variation of the radial width of cut with the cutting forces. The authors varied the feed rate so that the average cutting force remained constant for each value of the radial width of cut engaged. This is done in order to ensure the stability of the cutting operation. There is however no reference to how the radial width of cut was calculated. Hinduja et al. [20] calculated the instantaneous radial width of cut and approximated it by a stepped curve, thus enabling the toolpath to be subdivided into sections, the radial width and feed rate remaining constant over each section. If the radial depth of cut is lower than the cutting tool radius, the cutting tool would only be partially engaged and making a peripheral cut.

The most important factor in peripheral milling is to achieve a suitable feed per tooth, $f_z$. The feed value, $f_z$, has to compensate for the cutter engagement, which influences the chip thickness formed. Feed per tooth, $f_z$, should be multiplied by the modification factor. This will give a higher feed rate with a smaller arc of engagement, and at the same time ensure that the chip thickness is large enough as shown in Figure 1. However, the modification factor may not always be fully applicable because surface texture and climbing tendencies may limit the feed rate [21].

If the radial depth of cut is equal to the cutting tool diameter, the cutting tool is fully engaged and therefore it is making a slot cut. In turning and boring operations, a single-point tool cuts at a depth in relation to the workpiece radius. A large radial depth of cut will require a lower feed rate, or else it will result in a high load on the cutting tool thereby reducing the tool life. Therefore, a feature is often machined in several steps as the tool moves over the step over distance, and makes another cut at the radial depth of cut. In order to machine a feature that is wider than the width of a single cut, the tool must make several cuts, stepping to the side after each one. This step over distance is equal to the radial depth of cut for each cut and must be less than or equal to the tool diameter. The size of the step over distance will determine the scallop height between each step as can be seen in Figure 1. However, the research to date and from literature has revealed that up-until-now, the relationship between swept angle and energy demand has received little attention hence the focus and need for this research.

**1. 3. Research Aim and Objective** The aim of this work is to investigate and determine the optimum swept angle based on the specific cutting energy criterion in milling AISI 1045 steel alloy. This was to enable the identification of optimum cutting parameters and to evaluate the swept angle based on minimum cost and energy for process efficiency. In view of this, cutting tests were conducted by varying the undeformed chip thickness.

## 2. EXPERIMENTAL PROCEDURE

A set of 5 experiments was carried out on the Mikron HSM 400 machining center with a spindle HVC140-SB-10-15/42-3FHSK-E40 and Heidenhain TNC 410 NC controller. A tool holder E90X-D08-C10-06 with an overhang of 25mm having a single insert number SOMT-060204-HQ was used for the side milling operation in order to mimic the orthogonal cutting operation as previously reported in reference [14]. A Physical Vapour Deposition (PVD) general purpose multi-layered coated carbide insert with geometry shown in Table 1 was used for the side-milling test. The cutting parameters and chemical composition of the workpiece material is stated in Table 2. The machining test was conducted under a dry cutting environment. The electrical energy consumption was measured with a Fluke 435 power clamp meter attached to the main power buss at the back of the machine.

**TABLE 1.** Cutting tool geometry

| Geometry | Values |
|---|---|
| Nose radius (*μm*) | 400 |
| Edge radius (*μm*) | 60 |
| Positive Rake angle (*deg.*) | 5 |
| Rake face primary chip breaker land (*μm*) | 60 |

**TABLE 2.** Cutting parameters

| Material | AISI 1045 |
|---|---|
| Feed (*mm/tooth*) | 0.01 – 0.55 |
| Depth of cut (*mm*) | 3.5 |
| Cutting velocity (*m/min*) | 156 |
| Radial depth of cut (*mm*) | 0.2 – 1.00 |
| Tool diameter (*mm*) | 8 |
| Chemical composition (*Max*) | 0.46%C, 0.40%Si, 0.65%Mn, 0.40%Cr, 0.10 Mo, 0.40%Ni, 0.63% Others |
| Material Hardness | HV 146.4 |

## 3. RESULT AND DISCUSSIONS

The swept angles engaged for the cutting tests were evaluated based on Equations (1) and (2). The specific energy coefficient values were evaluated from the regression model as shown in Figures 3, 4 and 5 and tabulated in Table 1 with their corresponding specific energy values.

Table 3 show the specific energy coefficient evaluated from the corresponding Power-MRR trend curve shown in Figures 3, 4 and 5. This coefficient represents the electrical energy demand at the tool tip and it is a representation of the machinability index of the AISI 1045 alloy steel.

**TABLE 3.** Experimental data

| $f_z$ (*mm/tooth*) | $h_m$ average (*mm*) | Swept angle (*Radians*) | Swept angle (*Degrees*) | Specific cutting energy coefficient *k* (*J/mm$^3$*) |
|---|---|---|---|---|
| 0.010 | 0.002 | 0.318 | 18.2 | 7.803 |
| 0.100 | 0.022 | 0.45 | 25.8 | 3.734 |
| 0.190 | 0.051 | 0.555 | 31.8 | 2.772 |
| 0.460 | 0.143 | 0.644 | 36.9 | 2.098 |
| 0.550 | 0.19 | 0.723 | 41.4 | 6.00 |

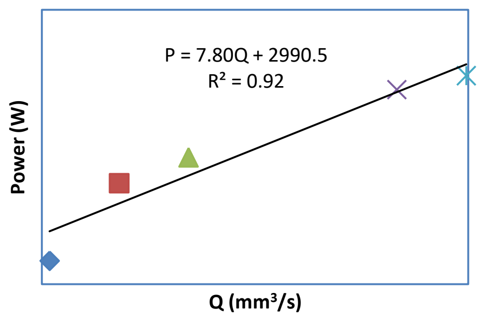


**Figure 3.** Power –MRR graph at 18.2$^0$ Swept angle

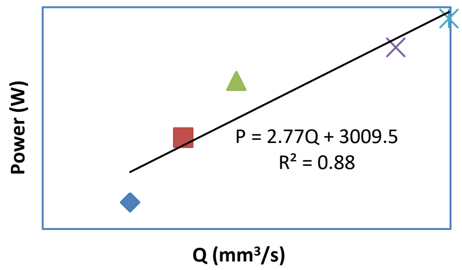


**Figure 4.** Power –MRR graph at 31.8$^0$ Swept angle

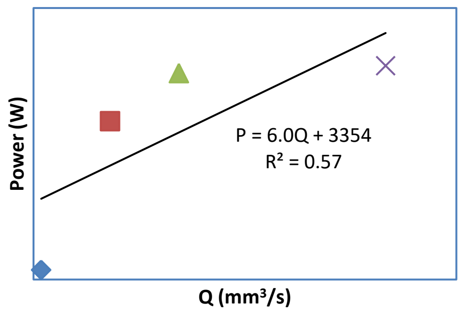


**Figure 5.** Power –MRR graph at 41.4$^0$ Swept angle

**3. 1. Optimum Swept Angle Estimation** In order to determine the optimum swept angle for machining AISI 1045 at minimum energy criterion, the specific energy coefficient obtained and tabulated in Table 3 are plotted against the variable swept angle values as shown in Figure 6.

From Figure 6, it can be seen that the optimum swept angle for the insert used for milling AISI 1045 steel alloy is 31.8$^o$ (i.e. 0.55 *radian*). At this angle, shearing will be dominant and this gives a total specific cutting energy for AISI1045 to be 2.77 $J/mm^3$. This value also is in line with the range found in literature [22]. At a feed $f_z$ of 0.55 *mm/tooth* (i.e. 0.19 *mm* undeformed chip thickness and a swept angle of 0.723 *radian*), the total specific cutting energy obtained is 6.0 $J/mm^3$.

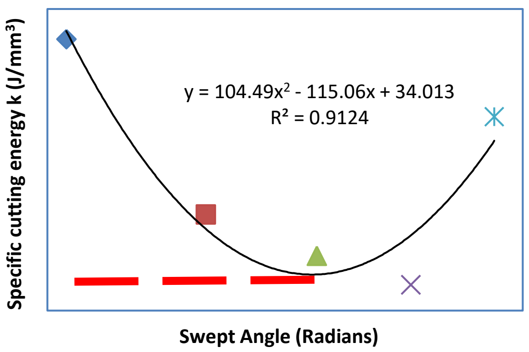


**Figure 6.** Optimum swept angle

Although the material removal rate at this point is higher and cycle time might be lower, the specific energy is comparably higher. This therefore increases the machining cost of the said alloy. However, at a value lower than 0.45 *radian* swept angle, the cutting operations will be within the ploughing dominated regime. The ploughing energy of any machining process can be estimated having known the optimum swept angle of machining that material.

Therefore, to evaluate the optimum swept angle equation based on minimum energy and minimum cost criterion, the regression model from Figure 6 is further analyzed. Considering Equation (3) and substituting the cutter diameter value of 8 *mm* (i.e. r = 4 *mm*) and optimum swept angle of 31.8$^o$, it then implies that; $a_e$ = 0.6 *mm*

To avoid ploughing effect occurrence, the swept angle must not be less than the optimum *Ø* as previously discussed. Therefore, from Equation (2):

$$\frac{h}{f_z} = \sin \emptyset = 0.53 \qquad (4a)$$

From Equation (4), it can be deduced that in order to avoid ploughing effect when machining AISI 1045, the undeformed chip thickness should be as stated in Equation (4b).

$$h = 0.53 f_z = No\ ploughing\ effect \qquad (4b)$$

where, *h* is the un-deformed chip thickness, $f_z$ is the chip load per tooth and $a_e$ is the step over or the radial depth of cut.

From Figure 6, the regression equation is as stated in Equation (5):

$$k = 104.49\emptyset^2 - 115.06\emptyset + 34.013 \qquad (5)$$

Differentiating Equation 5 and equate to zero in order to obtain the minimum and optimum swept angle value;

$$\frac{dk}{d\emptyset} = 0 = 208.98\emptyset - 115.06 \qquad (5b)$$

$$\emptyset_{opt} = 0.551 rad = 31.57^o \qquad (5c)$$

Substituting for *Ø* in Equation (5);

$$k_{opt} = 2.33\ Jmm^{-3} \qquad (5d)$$

The $k_{opt}$ value in Equation (5d) correspond with the lowest point of minimum specific energy where no ploughing effect is induced. Hence, for AISI 1045, the optimum swept angle must be 31.57$^0$ as deduced from Figure 6 and Equation 5d. This also proofs that the radial width of cut $a_e$ should not be less than *0.15 x r* otherwise from that point, machining would be within the ploughing dominated regime which translates to higher specific cutting energy values.

**3. 2. Validation of the Optimum Swept Angle for Machining AISI 1045 Steel Alloy** In order to further validate the optimum swept angle when milling

AISI 1045 steel alloy, the total power consumption were recorded for 18.2°, 31.8° and 41.4° different cutting swept angles. The energy demand (i.e. the area under the power-time curve for 18.2°, 31.8° and 41.4°) for $f_z$ of 0.01, 0.19 and 0.55 *mm/tooth* is as shown in Figures 7, 8 and 9.

From Figures 7, 8 and 9, the total electrical energy consumed can be evaluated considering the area under each of the power-time graph for each corresponding swept angle engaged. For example, and from Figure 8, the average power consumed when machining at 18.2° and 31.8° swept angles are 3109.41W and 3179.50W, respectively. The corresponding machining times are 22s and 16s, respectively.

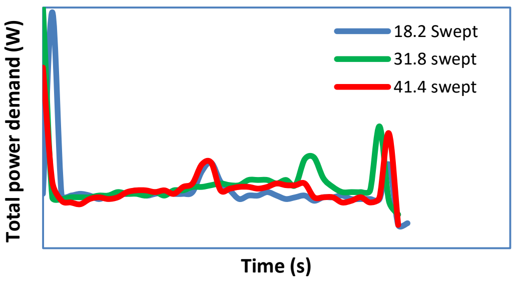


**Figure 7.** Total energy demand milling a toolpath at $f_z$ 0.01 *mm/tooth*

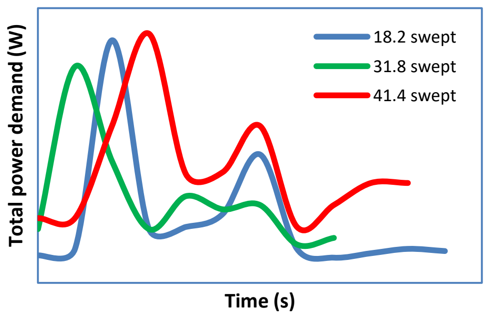


**Figure 8.** Total energy demand milling a toolpath at $f_z$ 0.19 *mm/tooth*

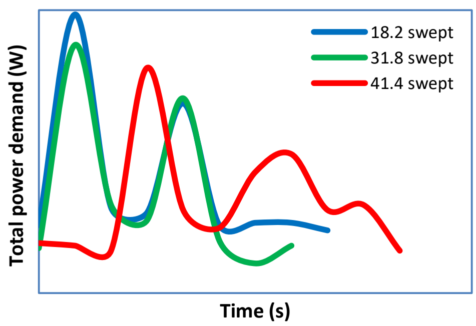


**Figure 9.** Total energy demand milling a toolpath at $f_z$ 0.55 *mm/tooth*

These values gave an average electrical energy demand of 190.02 Wh and 141.31 Wh. Hence, the total electrical energy demand at a feed of 0.19 *mm/tooth* are 190.02, 141.31 and 181.73 *Wh* for 18.2°, 31.8° and 41.4° swept angles respectively. It can be deduced that about 25% electrical energy can be saved between 31.8° swept angle when compared with 18.2° and 41.4° swept angles, respectively. Therefore, it is proposed that for sustainable milling of AISI 1045 steel alloy, the optimum swept angle should not exceed 31.8° and 0.19 *mm/tooth* feedrate should be adopted.

From the analysis, it can be seen that the theoretical optimum swept angle of 31.57° is well correlated with the actual swept angle of 31.8° obtained through the actual machining processes.

## 4. CONCLUSION

In this study, a new optimized value at which ploughing effects are minimal was developed. The values correspond to milling at swept angle of between 31.57° to 31.8° and at 0.19 *mm/tooth* feed. These values were derived to accommodate different cutting parameters for milling AISI 1045 steel alloy. These are the optimum parameters since the cutting plane exists within a value just above the ploughing and rubbing dominated regime. At these optimum values, electrical energy required can be reduced. Other conclusions derived from the study include:

1. It is therefore proposed that for sustainable milling of AISI 1045 steel alloy, the optimum swept angle of 31.57° should be adopted.
2. It can be deduced that about 25% energy can be saved when machining at 31.8° swept angle and at 0.19 *mm/tooth* feedrate.
3. Swept angle is an important characteristic for mechanical machining operations since it relates the cutting tool parameters, workpiece materials and the process parameters.
4. The ploughing energy of any machining process can be estimated with an adequate knowledge of the optimum swept angle for machining that workpiece material.
5. A pre-knowledge of the values of the specific ploughing energy can aid pre-process and resource efficient machining and energy resource management.

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**چکیده**

فرایندهای ماشینکاری مکانیکی، استراتژی تولید معمول برای مواد دوباره شکل یافته برای رسیدن به خصوصیات مورد نظر است. رویکرد مکانیکی، مکانیک فرایندهای ماشینکاری را با پارامترهای مختلف تعیین شده نشان داده است. هدف از این کار، بررسی تاثیر بهینه سازی زاویه جاروب و نفوذ آنها بر انرژی برش خاص برای فرز آلیاژ فولاد AISI 1045 است. این با تغییر گام، بیشتر از ارزش نرخ خوراک های مختلف به منظور تعیین معیار بهینه سازی برای ماشین کاری به دست می آید. مشاهده شده است که بهینه زاویه جاروب ۳۱/۸° در از بین بردن اثر شخم و کاهش انرژی برش خاص برای میزان بهینه سازی شده حداقل مناسب بود. با این حال، زاویه جاروب بالاتر از ۴۱/۴°، انرژی برش خاص با قدرت ماشین ابزار بالاتر را افزایش می دهد. این مربوط به کاهش در زمان چرخه، از طول مسیر ابزار کوتاه تر ناشی شده است. نتایج به دست آمده، بیشتر، پایه دانش را برای تعیین پارامترهای بهینه برای ماشین کاری پایدار و بهره وری منابع از محصولات تولید شده را توضیح می دهد.

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