RESEARCH ARTICLE OPEN ACCESS

Extraction of Electrical Energy from Heat Produced During Metal Cutting Operation on Lathe by Using Thermocouples

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ABSTRACT
Machining is the process of removal of excess material from the given work piece to finish it to the required dimensions required as per use. Various metals and alloys are machined with the help of cutting tools like HSS, carbides etc. Majority of the industry manufactured products require machining at some stage ranging from relatively rough or nonprecision work such as cleaning of sprues, risers and gates to high precision work involving tolerances of 0.0001 inch and high surface finish.
Machining operations on lathes involve rotating of work pieces and feeding of cutting tool against it in a specified manner with correct feed. This process involves constant rubbing of tool and work piece which generates a large amount of heat. This heat is usually carried away by the coolant or it is dissipated in the atmosphere.
With every passing day, the need for sustainable living on Earth is increasing greatly. For this we need to start extracting and recovering the lost energy. The following paper shows how electricity can be generated from the lost heat produced during machining operation on lathe by using thermocouples.
Keywords: Heat extraction; thermocouples; electrical energy.

I. Introduction

Today energy is extracted from various renewable and non-renewable resources by using advanced methods and equipments. None of the machines have 100% efficiency. The amount of energy supplied to the machine is not completely converted into work. Only a fraction of it is utilized to produce work while a few percentages are lost in overcoming losses like friction, linkage loss, transmission loss etc. And a portion of the energy always goes waste and is liberated in the form of heat, light, smoke or radiant energy. These waste energy by-products can be potentially converted to various other forms of energy and can be utilized further. This paper deals with extraction of electrical energy from heat liberated in different zones during metal machining on a lathe.

Chip formation

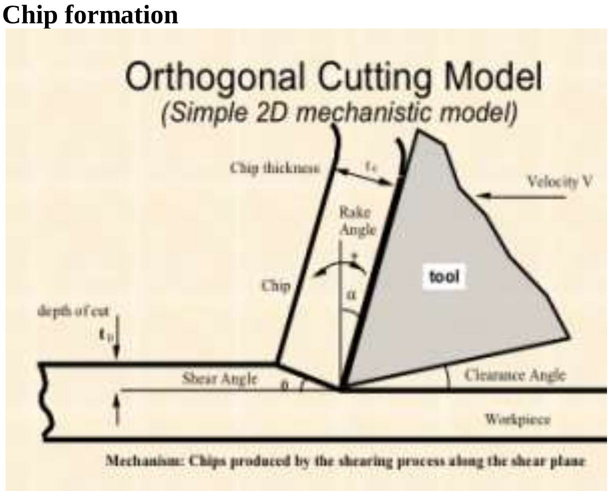


Figure 1 Schematic of orthogonal machining. The cutting edge of the tool is perpendicular to the direction of feed.

To understand this complex process the 3D (oblique) tool geometry into 2D (orthogonal) tool geometry. The workpiece is a flat plate. The workpiece is moving past the tool at velocity V. The feed of the tool is now called t, the uncut chip thickness. The depth of cut (DOC) is the width of the plate. The cutting edge of the tool is perpendicular to the direction of motion V. The angle that the tool makes with respect to a vertical from the workpiece is called the back rake angle α. The chip is formed by shearing. The shear plane angle, with respect to the horizontal, is φ. This model is sufficient to allow us to consider the behaviour of the work material during chip formation, the influence of the most critical elements of the tool geometry (the edge radius of the cutting tool and the back rake angle α), and the interactions that occur between the tool and the freshly generated surfaces of the chip against the rake face and the new surface as rubbed by the flank of the tool.

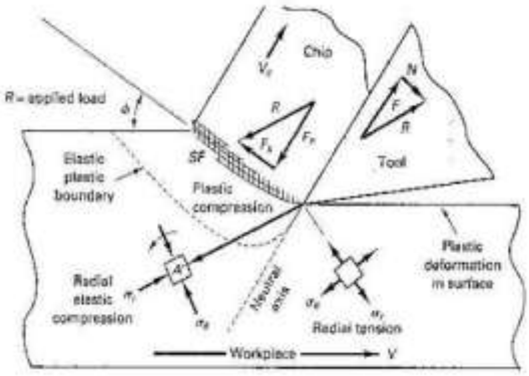


Figure 2 the machining process produces a radial compression ahead of the shear process.

Basically, the chip is formed by a localized shear process that takes place over a very narrow region. This large-strain, high-strain-rate plastic deformation evolves out of a radial compression zone that travels ahead of the tool as it passes over the workpiece. This radial compression zone has, like all plastic deformations, an elastic compression region that changes into plastic compression as the yield strength of the material is exceeded. The plastic compression generates dense dislocation tangles and networks in annealed metals. When this work hardening reaches a saturated condition (fully work hardened), the material has no recourse but to shear. The onset of the shear process takes place along the lower boundary of the shear zone defined by shear angle φ. The shear lamella (microscopic shear planes) lies at the angle ψ to the shear plane. This can be seen in a videograph and schematic made from Videograph as shown.

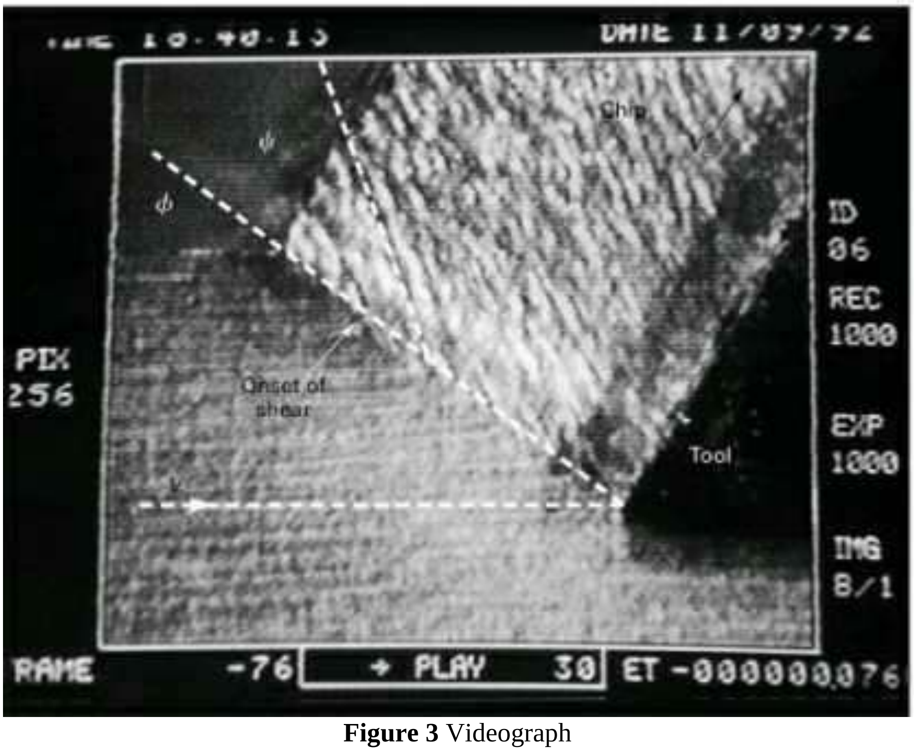


Figure 3 Videograph

The videograph was made by videotaping the orthogonal machining of an Aluminium plate at over 100X with a high-speed videotaping machine capable of 1000 frames per second. By machining at lower speeds (V= 8.125 rpm), the behaviour of the process could be captured and then observed in playback at very slow frame rates. The uncut chip thickness was t=0.020 inch. The termination of the shear process as defined by ψ cannot be observed in the still videograph but can be easily seen in the videos.

If the work material has hard second phase particles dispersed in it, they act as barriers to the shear front dislocations, which cannot penetrate the particle. The dislocation creates voids around the particles. If there are enough particles of the right size and shape, the chip will fracture through the shear zone, forming segmented chips. Free-machining steels, which have small percentages of hard second-phase particles added to them, use these metallurgical phenomena to break up the chips for easier chip handling.

Metal cutting parameters

There are various parameters and terminologies which are used to control the metal cutting process. They are as follows

Speed (V) – It is the primary cutting motion, which relates the velocity of the cutting tool relative to the workpiece. It is generally given in units of meters per minute (m/min) or meters per second (m/s).

Mathematically **Speed (V) =** $\frac{\pi DN}{1000}$

Where D is in mm, V is speed in surface mm per minute, and N is the revolutions minute (rpm) of the workpiece. The input to the lathe will be in revolutions per minute of the spindle.

Feed (f_r) – It is the amount of material removed per revolution or per pass of the tool over the workpiece. In turning, feed is in mm/rev, and the tool feeds parallel to the rotational axis of the workpiece. Depending on the process, feed units are mm /rev, mm/ cycle, mm /minute, mm / tooth.

Depth of cut (DOC) - It represents third dimension. In turning, it is the distance the tool is plunged into the surface. It is the difference in the diameter D1, the initial diameter, and D2, the final diameter.

Mathematically **DOC =** $\frac{D1-D2}{2} - D$

Metal removal rate (MRR)

Once cutting speed V has been selected, Equation N = 1000 V/ πD is used to determine the spindle rpm, N. The speed and feed can be used with the DOC to estimate the metal removal rate for the process, or MRR.

For turning, the MRR is

$$\mathbf{MRR = 1000\ V\ f_r d\ \ [mm^3/min]}$$

This is an approximate equation for MRR. For turning, MRR values can range from 2.5 to 15240 mm3/min. The MRR can be used to estimate the power needed to perform a cut, as will be shown later. For most processes, the MRR equation can be viewed as the volume of metal removed divided by the time needed to remove it.

$$\mathbf{MRR} = \frac{volume\ of\ cut}{\mathrm{Tm}}$$

MRR = volume of cut / T_m

Where T_m is the cutting time in minutes. For turning, the cutting time depends upon the length of cut L divided by the rate of traverse of the cutting tool past the rotating workpiece f_rN. Therefore

$$\mathbf{T_m} = \frac{\mathrm{L + allowance}}{\mathrm{fr\ N}}\ \ \mathbf{[min]}$$

An allowance is usually added to the L term to allow for the tool to enter and exit the cut.

TABLE 20-1 Shop Formulas for Turning, Milling, Drilling, and Broaching (English Units)

Parameter	Turning	Milling	Drilling	Broaching
Cutting speed, fpm	$V = 0.262 \times D_t \times$ rpm	$V = 0.262 \times D_m \times$ rpm	$V = 0.262 \times D_d \times$ rpm	V
Revolutions per minute, N_s	rpm = $3.82 \times V_c/D_t$	rpm = $3.82 \times V_c/D_m$	rpm = $3.82 \times V_c/D_d$	—
Feed rate, in./min	$f_m = f_r \times$ rpm	$f_m = f_t \times$ rpm	$f_m = f_r \times$ rpm	—
Feed per rev tooth pass, in./rev	f_r	f_t	f_r	—
Cutting time, min, T_m	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/f_m$	$T_m = L/12V$
Rate of metal removal, in.^{3}/min	MRR = $12 \times d \times f_r \times V_c$	MRR = $w \times d \times f_m$	MRR = $\pi D^2 d/4 \times f_m$	MRR = $12 \times w \times d \times V$
Horsepower required at spindle	hp = MRR × HP_s	hp = MRR × HP_s	hp = MRR × HP_s	—
Horsepower required at motor	hp_m = MRR × HP_s/E	hp_m = MRR × HP_s/E	hp_m = MRR × HP_s/E	hp_m = MRR × HP_s/E
Torque at spindle	t_s = 63,030 hp/rpm	t_s = 63,030 hp/rpm	t_s = 63,030 hp/rpm	—
Symbols	D_t = Diameter of workpiece in turning, inches D_m = Diameter of milling cutter, inches D_d = Diameter of drill, inches d = Depth of cut, inches E = Efficiency of spindle drive f_m = Feed rate, inches per minute f_r = Feed, inches per revolution f_t = Feed, inches per tooth hp_m = Horsepower at motor MRR = Metal removal rate, in.^{3}/min		hp = horsepower at spindle L = Length of cut, inches n = Number of teeth in cutter HP_s = Unit power, horsepower per cubic inch per minute, specific horsepower N_s = Revolution per minute of work or cutter t_s = Torque at spindle, inch-pound T_m = Cutting time, minutes V = Cutting speed, feet per minute w = Width of cut, inches	

Values for specific horsepower (unit power) are given in Table 20-4.

Merchant's Model

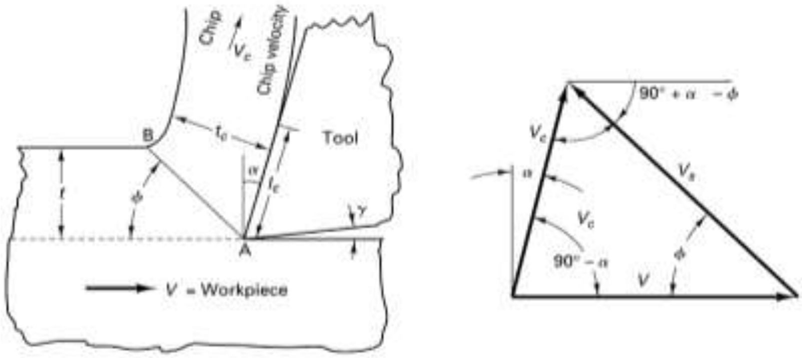


Figure 4 Merchant's Model

Velocity diagram associated with Merchant's orthogonal machining model.

Assume that 1) the shear process takes place on a single narrow plane as A-B in figure. Tools cutting edge is perfectly sharp and no contact is being made between the flank of the tool and the new surface.

Chip thickness ratio:

$r_c = t / t_c = (AB \sin φ)/[AB \cos(φ - α)]$,

or

$\tan φ = (r_c \cos α)/(1 - r_c \sin α)$

Where AB – length of the shear plane from the tool tip to the free surface.

For consistency of volume,

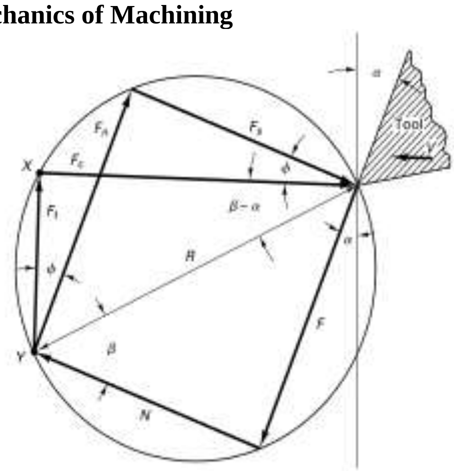
$r_c = t / t_c = (\sin φ) / [\cos(φ - α)] = V_c./V$,

and

$V_s / V = (\cos α) / [\cos(φ - α)]$

Where V – velocity for workpiece pasing tool, Vc – chip moving velocity, V_s – shearing velocity, φ – onset of shear angle, α - rake angle

Mechanics of Machining



Friction force F and normal force N are:

$F = F_c \sin α + F_t \cos α$, $N = F_c \cos α - F_t \sin α$ and $β = \tan^{-1} μ = \tan^{-1} (F/N)$,

Where m - friction coefficient

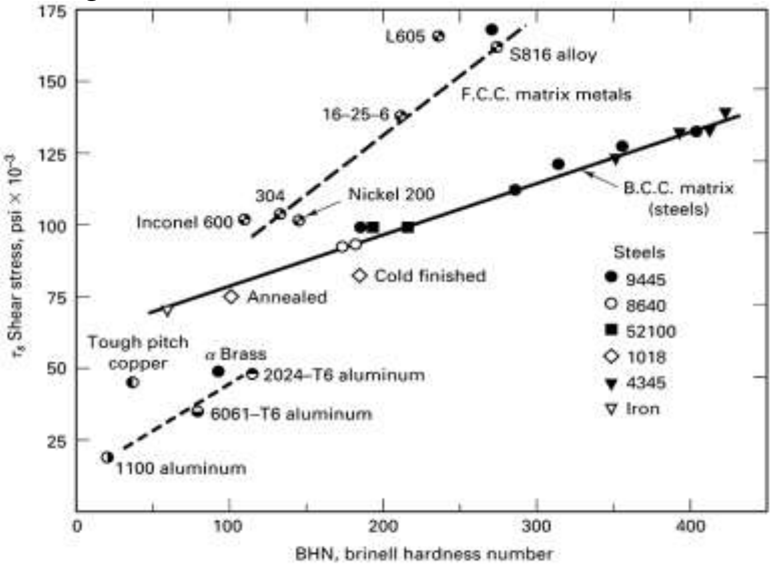
α nd β – the angle between normal force N and resultant R.

If a = 0, then $F = F_t$, and $N = F_c$ **.** in this case, the friction force and its normal can be directly measured by dynamometer.

$R = \sqrt{(Fc2 + Ft2)}$, $F_s = F_c \cos φ- F_t \sin φ$, and $F_n = F_c \sin φ + F_t \cos φ$,

Where F_s is used to compute the shear stress on the shear plane

Effect of hardness on heat generation



From the above graph of shear stress τ_s vs. variation with Brinell hardness number (**BHN**) for variation steels and aerospace alloys. The following observations were made.

Steels 9445, 8640, 52100, 1018 4345 alloys has almost linear relation of shear stress with BHN and it was observed that a line drawn joining all these points has a slope of 19.5~20 degree. With large increase in BHN shear stress τ_s increases by small amount for **BCC** (body-centered cubic) matrix steels. Now a line is drawn joining all **FCC** (face-centered cubic) matrix metals and it was observed that the slope of the line joining all points is 40 degrees which gives a close linear equivalence relationship between BHN and shear stress τ_s. BHN increases with the same amount with respect to shear stress.

So equal amount of increase in BHN for both BCC and FCC matrix increase in shear stress τ_s was larger in case of FCC matrix metal. Since it takes more power and force to deform the metal and cause plastic deformation, so heat generated will be more in case of FCC matrix metal.

In conclusion that *heat generation is purely a function of shear stress τ_s required to deform the metal and BHN. It also depends on the coefficient of friction* $\boldsymbol{\mu}$

Heat generated H = f (τ_s, BHN, μ)

It also depends on secondary factors like *cutting speed* ***V****, depth of cut* ***DOC*** *and feed* $\boldsymbol{f_r}$ *which in turn increases the friction μ and shear stress* $\boldsymbol{\tau_s}$ resulting in more heat generation.

So considering all major and minor factors we can say that heat **H** is a function of the following

Heat generated H = f (τ_s, BHN, μ, V, DOC, f_r)

Role of variation of the various machining parameters on cutting temperature

The magnitude of cutting temperature is more or less governed or influenced by all the machining parameters like:

- Work material: - specific energy requirement, ductility and thermal properties (**λ, c_v**)
- Process parameters: - cutting velocity (**V_C**), feed (**f_r**) and depth of cut (**t**)
- Cutting tool material: - thermal properties, wear resistance and chemical stability
- Tool geometry: - rake angle (**γ**), cutting edge angle (**φ**), clearance angle (**α**) and nose radius (**r**)
- Cutting fluid: - thermal and lubricating properties, method of application

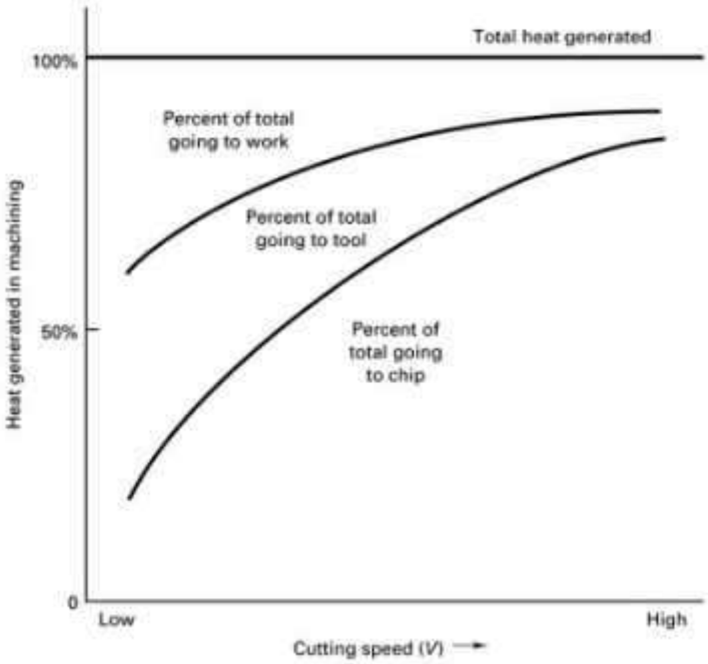
Following equation shows the effects of the various parameters on cutting temperature.

$$\theta_i = \frac{C_\theta (V_c)^{0.4} (s_o \sin\varphi)^{0.24} (t)^{0.105}}{\left(\frac{t}{So}\right)^{0.086} (r)^{0.11} (ts_o)^{0.054}}$$

Where, C_θ = a constant depending mainly on the work-tool this equation clearly indicates that among the process parameters V_C affects θ_i most significantly and the role of t is almost insignificant. Cutting temperature depends also upon the tool geometry. It depicts that θ_i can be reduced by lowering the principal cutting edge angle, φ and increasing nose radius, r. Besides that the tool rake angle, γ and hence inclination angle, λ also have significant influence on the cutting temperature. Increase in rake angle will reduce temperature by reducing the cutting forces but too much increase in rake will raise the temperature again due to reduction in the wedge angle of the cutting edge. Proper selection and application of cutting fluid help reduce cutting temperature substantially through cooling as well as lubrication.

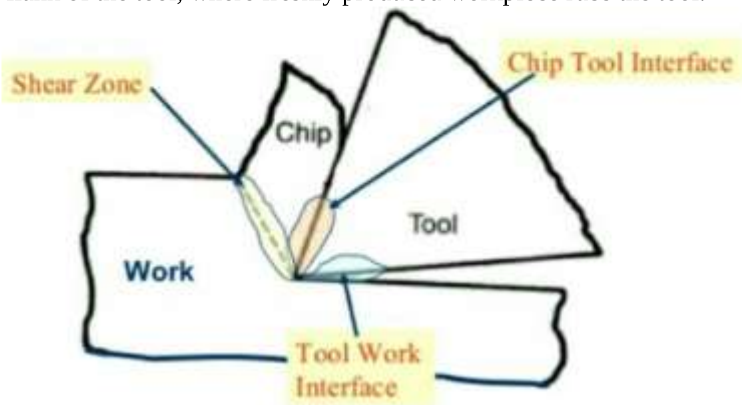
Heat generation in metal cutting

In metal cutting, the power put into the process (F_CV) is largely converted to heat, elevating the temperatures of the chip, the workpiece and the tool. These three elements of the process, along with the environment (which includes the cutting fluid), acts as heat sinks. Following graph shows distribution of heat to these three sinks as a function of cutting speed.



The three main source of heat are listed below in the order of their heat generating capacities

a) **Zone 1:** The shear process itself, where plastic deformation results in the major heat source. Most of this heat stays in the chip.
b) **Zone 2:** The tool-chip interface contact region, where additional plastic deformation takes place in the chip and there is considerable heat generated due to sliding friction.
c) **Zone 3:** The flank of the tool, where freshly produced workpiece rubs the tool.



Zone 1 : *Primary zone or shear zone*

This is called primary zone because maximum amount of heat is generated in this zone. The heat generated in this zone is mainly due to plastic deformation of the workpiece metal. A large portion of the energy used in cutting is converted into heat during the course of deformation the workpiece metal, and nearly 80% of this heat is carried away by the chip and coolants used, while the remaining is conducted into the tool and the workpiece metal.

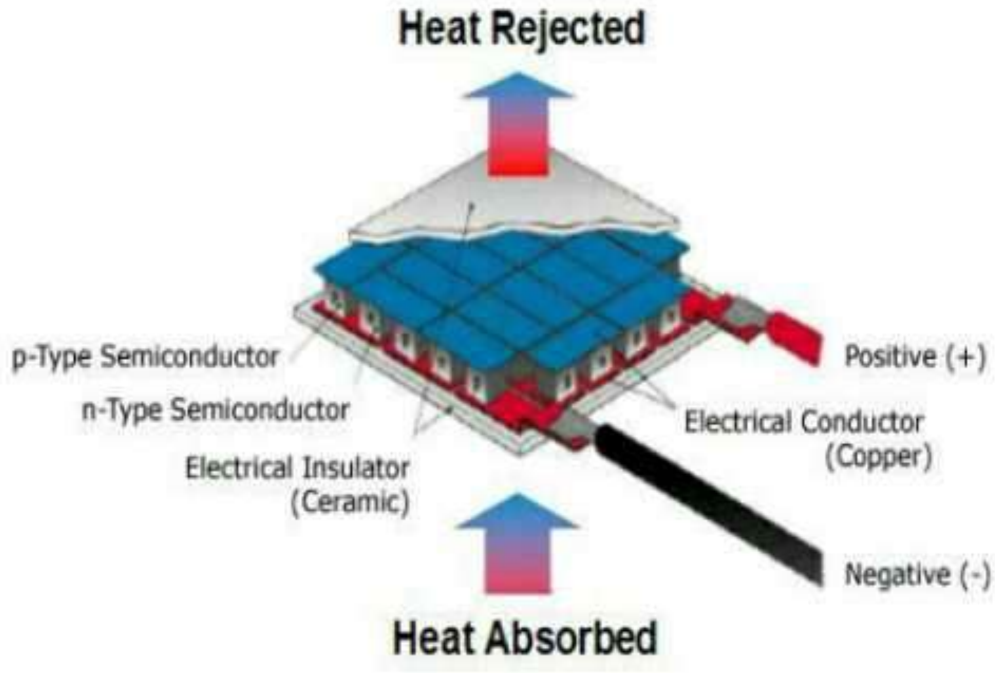
Zone 2 : *Secondary zone or Tool-chip interface zone*

As the deformed chip slides upwards across the tool face, heat is generated due to the friction between chip and tool face. This further raises the temperature of the chip. A part of heat thus generated here is conducted into the tool. The temperature at the tool-chip interface increases with the cutting speed and feed. This also increases the temperature of the cutting tool.

Zone 3 : *Tool-work interface zone*

During metal cutting, the tool rubs against the surface of the workpiece resulting in heat generation due to friction. However, the heat generated at the tool-work interface forms only a small portion of the total heat generated, because sufficient clearance angle is always provided on the tool to minimize the rubbing action. However, it is important to note that, once the cutting starts, the wear on the tool also starts, and hence, the region between the tool and the workpiece becomes a serious heat source. Hence, the cutting parameters like speed, feed depth of cut and the tool geometry form the main criteria in the formation of heat in this zone.

Thermocouples



A thermoelectric generator is a device that consists of a p-type and n-type semiconductors connected in series. This structure can be used to convert heat energy to electricity by using a principle known as the Seebeck effect. When heat is applied to one surface of the thermoelectric generator, the electrons in the n-type semiconductor and the holes in the p-type semiconductor will move away from the heat source. This movement of electrons and holes gives rise to an electrical current. The direction of the current is opposite to the movement of the electrons, and in the same direction as the movement of the holes. By creating the appropriate electrical connections, the current of the thermoelectric generator flows in a closed loop through the p-type and n-type semiconductors and an external load. This pair of n-type and p-type semiconductors forms a thermocouple. A thermoelectric generator can consist of multiple thermocouples connected in series, which increases the voltage output, and in parallel to increase the current output

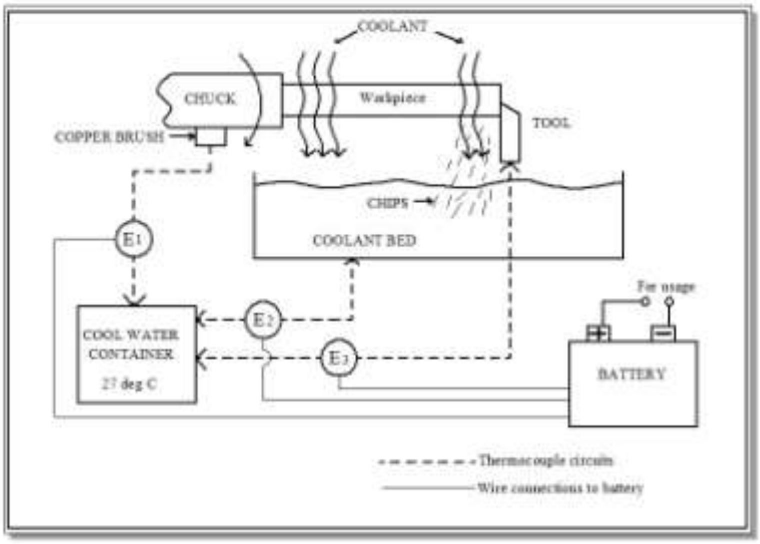
When two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, there is a continuous current which flows in the thermoelectric circuit.

$$\mathbf{E_{emf} = S\ \Delta T}$$

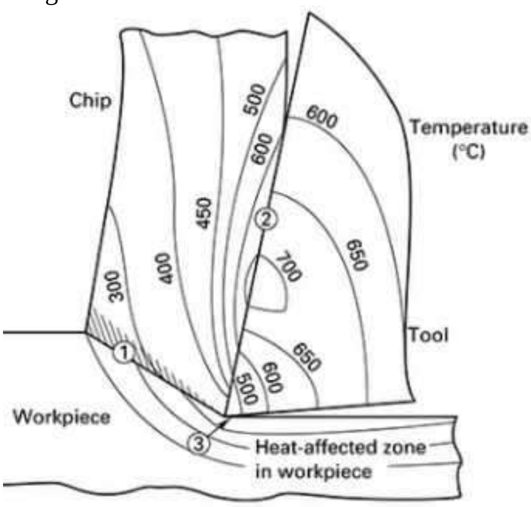
Where E_{emf} is the emf generated, S is the Seebeck coefficient and ΔT is the gradient in temperature

Extraction of electrical energy from Heat zones using Thermocouple circuits

II. CIRCUIT DIAGRAM OF EXPERIMENT



The figure shows the block diagram of the experiment. It consists of a workpiece mounted on a chuck. A cutting tool does the cutting operation. A coolant bed is placed below the workpiece such that all the chips formed during cutting, falls into the coolant bed along with coolant. A copper brush is placed in contact with the chuck. A cool water container is filled with water at room temperature (27 deg C) which acts a Low temperature junction J1. The major sources of heat are Chips (60%) , Cutting Tool (30%) , Midsection of workpiece (10%) and Coolant bed.
The ends of all these heat sources are connected to one end of thermocouple circuit which acts as High temperature junction J2. The emf generated in each circuit is sent to a main battery which stores the charge for further use.



Temperature in different zones of metal

Now the heat is extracted economically from the following sources

1. Chips and coolant bed
2. Cutting Tool
3. Chuck

1. Heat extraction from Chips and Coolant bed

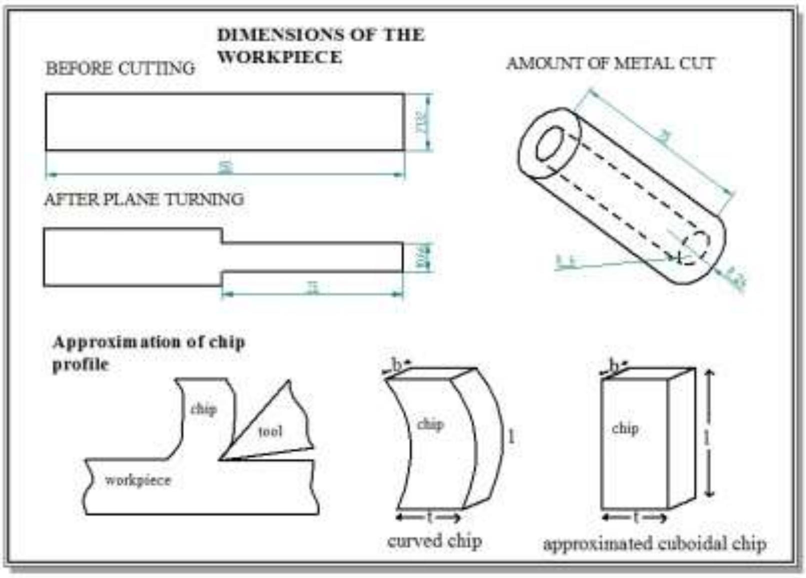
Chips accounts for 60% of the heat generated during machining which has high potential to be converted to electrical energy. The following system extracts maximum heat from the workpiece. The workpiece which is at room temperature (27 deg C or 300 K) is cut using a single point cutting tool. Due to shear force plastic deformation large heat is produced. This heat is stored in the chips in the form latent heat and a portion of it is conducted to the workpiece. The heated chip falls into the coolant bed and its heat is transferred to the coolant. A small amount of coolant is also poured over the midsection to absorb the heat conducted to the metal. The combined effect of the heat extracted from midsection and chips flows into the coolant bed. The outer surface of the coolant bed is covered with an adiabatic wall with the help of materials like mineral wool, thermocole etc. Considering losses we can conclude that 80% of the heat produced is transferred from chips and workpiece to the coolant bed and the remaining is dissipated to the atmosphere during the time chips and coolant falls into coolant bed.

Calculations for heat transfer from Coolant and Chips to Coolant bed

Let us assume

The initial dimensions of the workpiece are D_i = 24 mm = 0.024 m
Length of the workpiece is L = 150 mm = 0.15 m

Plane turning operation is performed on the workpiece and it is cut into as shown



The amount of material removed during plane turning is as shown. It is converted to chips during cutting. The curved chip is approximated to a cuboidal chip for calculation of volume.

(Number of chips N_C x Volume of 1 chip) = Volume of the workpiece removed

N_C x volume of 1 chip = $\pi (R^2 - r^2) h$ (eq – 1)

$= 3.14 \times ((0.012)^2 - (0.006)^2) \times 0.075$

$= 2.5434 \times 10^{-5}\ m^3$

The chip thickness (a_2) usually becomes larger than the uncut chip thickness (a_1). The reason can be attributed to

$$\zeta = \frac{a2}{a1} > 1.00\ (since\ a2 > a1)$$

where, ζ = chip reduction coefficient

Therefore a chip has a curved profile with $a_2 > a_2$

By approximating the curved shape of a chip to a rectangular block and measuring the dimension of a chip under profile projector we get

Length = 10 mm = 0.01 m thickness = 0.5 mm = 0.0005 m

Breadth (depends on the width of the cutting portion of the tool = 5 mm = 0.005 m

Therefore volume of a chip $V_{chip} = 0.01 \times 0.0005 \times 0.005 = 2.5 \times 10^{-8}\ m^3$

$N_C \times 2.5 \times 10^{-8} = 2.5434 \times 10^{-5}$ (From eq – 1)

$N_c = 1017.3 \sim 1017$ chips

We know that $\boldsymbol{\rho = \frac{m}{v}}$ $m = \rho\ v$

Mass of 1 chip = $2.5 \times 10^{-8} \times 7000$ (roughly density of cast iron 7000 kg/m^3)

Mass of 1 chip = 1.75×10^{-4} kg

Mass of 1017 chips = $1017 \times 1.75 \times 10^{-4}$ = 0.1779 kg = 177.9 ~ 178 grams

Heat contained in all the chips $Q_c = m\ c\ \Delta T$

Since c for cast iron is 450 J/0 deg for 1 KG

$\Delta T = t_2 - t_1 = 723\ K - 300\ K$ because the average cutting temperature of chip is 723 K

$Q_c = 0.1779 \times 450 \times 423$ = 33863.265 J = 33.86 KJ

This is the total heat of the chips generated during the cutting process

Now if we consider 20% loss of heat due to dissipation during transition to coolant bed we get

$Q_c = Q_T + Q_L$ Where Q_T is the heat transmitted to next stage and Q_L is heat lost

Q_L = (20%% of Q_c) = m c ΔT

$Q_L = 6772.653 = 0.1779 \times 450 \times (723 - t)$

t = 638.4 K

So $Q_T = 33863.265 - 6772.653 = 27090.612$ J

Now 27090.612 is the heat transferred by chips to coolant bed.

This results in final temperature of coolant bed as follows

$Q_T = 27090.612 = m_{coolant}\ c_{coolant}\ \Delta T$

$Q_T = 27090.612 = 10 \times 4118.8 \times (638.4 - t_{coolant})$

We use RUSTLICK SS-405L Semi-Synthetic Coolant which has the following specifications

m = 10 kg c = 4118.8 J/ kg K

therefore $t_{coolant} = 637.742$ K

we observe that 99.95 % of the heat from the chips falling into the coolant bed is absorbed by the coolant.

Since the thermoelectric generator uses chromel-alumel thermocouple the measured Seebeck coefficient is then a contribution from both the metals and can be written as:

$$S_{AB} = S_B - S_A = \frac{\Delta V_B}{\Delta T} - \frac{\Delta V_A}{\Delta T}$$

Seebeck coefficient *S* of a high-purity Cr specimen ($\rho_{273}/\rho_{4.2}$=380)
Seebeck coefficient S of a high-purity Al specimen (($\rho_{273}/\rho_{4.2}$=-1.5)
S_{AB} = 380-(-1.5) = 381.5 µV/K
Eq .2

In general, the Seebeck effect is described locally by the creation of an electromotive field

$$\mathbf{E}_{\mathrm{emf}} = -S\nabla T$$

Where S is seebeck coefficient and ∇T is the gradient in temperature T.(637.742-300)K
E_{emf} = 381.5 x 337.742 = 128848.573 µV = 0.12884 V

The amount of emf generated depends on the seebeck coefficient, temperature difference, time of cutting, coefficient of friction, cutting parameters etc. The amount of emf generated can be controlled or increased by using a thermocouple of higher seebeck coefficient and obtaining high temperature difference.

2. Heat extraction from cutting tool

Cutting tool accounts for 30% of the heat generated during machining which has high potential to be converted to electrical energy. The following system extracts maximum heat from the cutting tool. The cutting tool which is at 650 deg C or 923 K is used for cutting workpiece. Due to shear force plastic deformation of workpiece metal and friction between tool and workpiece, large heat is produced. This heat is dissipated to various portions of cutting tool. A small amount of heat is carried away by the coolant which is also poured in the cutting zone. The heat so accumulated in the cutting tool is extracted using thermoelectric generator. One end of the circuit is connected to the cutting tool which acts as High-temperature junction and the other end is connected to the water container which acts as a low-temperature junction. Considering losses we can conclude that 20% of the heat is lost by radiation to the atmosphere.

Calculations for emf generated due to temperature difference of cutting tool and water container

Since the average temperature at the cutting tool surface after considering the losses we have T_{tool} = 600 C or 873 K
Temperature of the water container is T_{water} = 27 C or 300 K
Now the gradient in temperature is $\Delta T = T_{tool} - T_{water}$ = 573
From Eq .2 S_{AB} = 380-(-1.5) = 381.5 µV/K

$$\mathbf{E}_{\mathrm{emf}} = -S\nabla T$$

So emf generated due to heat generated at cutting tool surface is given by
E_{emf} = 381.5 x 573 = 218599.5 µV = 0.2185995 V

Again this emf generated depends on seebeck coefficient, temperature difference, time of cutting, coefficient of friction, cutting parameters etc. The amount of emf generated can be controlled or increased by using a thermocouple of higher seebeck coefficient and obtaining high temperature difference.

Also higher temperature difference can be obtained by placing the terminal of thermoelectric generator at the highest temperature zone mostly at the middle of the tool near the point of contact between the chip and tool. The temperature is high in this zone because the shear deformation takes place and also the chip gets rubbed to the cutting tool. This results in increase in value of ΔT and hence increases the amount of emf produced.

3. Heat extraction from chuck

Chuck of the lathe also has a little potential to generate electricity due to small amount of heat present in it. This heat is not mainly due to the heat generated during the metal cutting process. The lathe running at high rpms causes heat build up which is conducted to chuck. Also since the chuck holds the hot workpiece, a part of the heat is transferred to chuck. This also accounts of additional heat accumulation in chuck

This heat can be harvested by placing a copper brush in contact with the chuck. As the chuck rotates, the copper brush gets rubbed on the chuck surface and the heat in the chuck is conducted to the copper brush this acts as High-temperature zone. The end of the copper brush is connected to the thermoelectric circuit whose other end is dipped in water container which maintained at 27deg C. Also the constant rubbing of copper brush also generates heat due to friction. This raises the temperature further more. Considering losses 50-60% heat is lost to atmosphere during rotation and is radiated to atmosphere.

Copper brush used in heat extraction from chuck

Here heat generate is a function of heat from workpiece (H_W), heat from the lathe (H_L) and heat due to friction (H_F)
Heat generated at chuck **$H = f(H_W, H_L, H_F)$**

Calculations for emf generated due to temperature difference of chuck and water container

Since the temperature of the chuck is roughly around 35-40 degree C. By considering the heat generated to due to friction we get temperature of chuck T_{chuck} = 60 deg C or 333 K
Temperature of the water container is T_{water} = 27 C or 300 K
Now the gradient in temperature is $\Delta T = T_{chuck} - T_{water} = 33$
From Eq .2 S_{AB} = 380-(-1.5) = 381.5 µV/K

$$\mathbf{E}_{\mathbf{emf}} = -S\nabla T$$

So emf generated due to heat generated at chuck is given by

E_{emf} = 381.5 x 33 = 12589.5 µV = 0.0125895 V

Since this emf generated is very small but this accounts for a little electricity generation. The reason to extract heat from all the heat zones is to maximise the efficiency of machine and hence prevent wastage of heat. The waste heat from all the heat zones is converted to electricity and is stored in a battery from where power is taken for further use.
The gradient in temperature can be increased by increasing the temperature difference. This is done by

1. ***Increasing the higher temperature at high-temperature junction***

This is achieved by increasing the cutting speed, feed rate, MRR, coefficient of friction, complete extraction of heat from all the sources, using a coolant of high heat capacity which can absorb more heat etc

2. ***Decreasing the lower temperature at low-temperature junction***

This is achieved by lowering the temperature of water container by adding ice, keeping it away from the heat source, protecting it by creating an adiabatic wall around it with the help of materials like industrial mineral wool and thermocole.
Larger the temperature gradient, larger is the emf generated. Also a material with high seebeck coefficient also aids in generation of high emf.

Increased efficiency of lathe due to emf generation

Efficiency $\eta = \frac{work\ output}{power\ input}$

Consider a Turnmaster Series lathe with Spindle Power Rating 10 hp = 10 x 745.6998
Power input = 7456.99 ~ 7457 watts

This includes power input from all the sources like control system power supply, lubrication system pump motor drive, cutting zone lighting, auxiliary drive units, feed motion drive units, coolant pump drive unit and positioning motion drive units.
Let power output be = P watts.
So **efficiency** $\eta = \frac{P}{7457}$ **X 100** **= 0.01341 P %** ....equation 3
Now taking the amount of electricity produced into consideration we get
Let net electricity produced = E units
So total power output considering the emf = P + E
Now new **efficiency** $\eta_{new} = \frac{P+E}{7457}$ **x 100** = **0.01341(P+E) %** ....equation 4
Comparing equation 3 and 4 we observe that efficiency η_{new} is more when compared to efficiency η due to conversion of waste heat into electricity.

Hence the efficiency of lathe is increased due to generated electricity

Advantages of this System of Electricity generation

1. System is cheap since thermocouple is easily available and is inexpensive
2. Increases the efficiency of the machine
3. Generated electricity is used to run lights and other components
4. It is eco-friendly since the waste heat is converted to electricity thereby reducing the amount of heat radiated and prevents global warming. It also prevents loss of habitat and does not disturb ecosystem.
5. This system can be used in remote and hilly areas to light bulbs where there is shortage of electricity
6. This saves the non-renewable sources of energy like fossil fuels
7. System is one-time installation and runs for years with very less maintenance
8. This system can be used to generate large amount of electricity in industries and workshops where there are large number of lathes
9. Additional accessories like step up transformer can be used to increase the voltage

III. RESULTS

In this project, the heat produced during machining at different heat zones is converted to electricity by using thermoelectric generators (T.E.G) this waste heat was utilized and converted to electricity. The major heat sources were chips (60%), cutting tool (30%) and chuck (5-10%). These heat sources were used as high temperature junctions and all these sources were connected one end of TEG. The heat from chips was extracted using a coolant bed which was connected to TEG. Heat from the tool was extracted by a simple circuit without the aid of cooling bed. The heat from chuck was extracted by placing a copper brush in contact with the chuck. The end of the Cu brush was connected to a TEG. There was a low temperature zone kept which was a container of water maintained at room temperature and was adiabatically sealed. The other end of TEG was connected to this low temperature junction. The difference of temperature gradient produced an emf which was conveniently extracted from all the sources and was fed to a battery storage system which stored the generated charge. The generated emf was stored and experimental observations were made. Calculations of emf generated in each of the 3 cases were done. Finally the efficiencies of the lathe were determined with and without considering the electricity generated. And it was found that the efficiency of lathe with electricity produced with this system was found to be more than efficiency of lathe without electricity generation system.

IV. CONCLUSION

Thermoelectric generation can be a suitable energy source in space, remote areas, industries, especially in situations where energy and resource conservation is taken into consideration. An alternative energy source is photovoltaics, which actually have a much higher efficiency (up to approximately 40%, as compared to approximately 5% for a thermoelectric generator). However, for deep-space missions, a thermoelectric generator can provide power where a solar cell would fail. In addition, thermoelectric generators are relatively inexpensive, easy to handle, and robust, as they are solid-state devices with no moving parts. In conclusion, these thermoelectric generators are useful in electricity generation in areas where large amount of heat is radiated or is lost for example industries, factories, labs workshops etc. It has a good potential to be converted to electricity.

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