Study of Temperature Profile and its Effect on Surface Roughness of Expanded Polystyrene Foam during Hot Wire Slicing

Sandeeep Dasgupta[1] Dr. S. A. Mastud[2] Ranjit Kumar[3] Prof. K. P. Karunakaran[4]
[1,2]Department of Mechanical Engineering
[1,2]VJTI, Mumbai-400019 [3,4]IIT, Bombay, Mumbai-400076

Abstract— Expanded Polystyrene (EPS) or Plastic foam, commonly known as thermocol is used mainly for packaging and insulation purposes. Another important usage is pattern making for lost foam casting. Our focus in this paper will be restricted to the latter purpose. Hot tool is used for making various intricate shape easily and in lesser time. Moreover, the hot tool cutting process involves minimum cutting force compared to mechanical cutting. In this process nichrome wire is used as cutting tool which is heated by passing electricity through it. Nichrome wire diameter, feed rate and supply voltage are taken as input variable in the experiment whereas surface roughness as output variable. This paper explores into the plastic foam cutting process with a number of experimental cutting trials (more than 100), at different values of input variable and finding the effect of input variables on surface roughness. The objectives of the paper are to establish a mathematical model for steady state hot wire temperature and verify the same with experiment and to find out optimum input variables at which surface roughness is minimum. Surface roughness was measured using contact type profilometer.

Key words: Hot-Wire Cutting, EPS, Surface Roughness, Ablation, Temperature Profiling

I. INTRODUCTION

Plastic foam is widely used across the industries for various purposes from packaging, support material against damages during transit, thermal insulation, disposable utensils etc. The most common forms of plastic foam are extruded polystyrene (XPS) and expanded polystyrene (EPS). Both materials are lightweight and are readily available in standard block or sheet forms. Both of these are manufactured using casting and extruding processes [1].In these processes various shapes, sizes and profiles are created. Moreover, hot tool cutting process also produces complex shapes, sizes and profiles as an alternative to the existing processes. In addition to that thetime consumption and power requirement in this process are very less compared to the conventional cutting process. There are various types of foam slicing machines are available [2]. In these machines the process is achieved by introducing a heat source (generally a wire) which alters the physical state of the plastic foam and allows cutting process to be completed. Heat source is generated by passing an electrical current through a cutting element or 'hot-wire'. Surface roughness depends upon the diameter of the hot wire, supply voltage and feed rate at which hot wire is driven into the EPS block. Surface roughness determines whether the job will be accepted or rejected.

II. OBJECTIVES

The objectives of this research paper are as follows:

1) To make a mathematical model of nichrome wire temperature in open air and during cutting.
2) Verify the model using with experimental data at various combination of input condition.
3) Quantitatively measure outputvariable i.e. surface roughness at various feed rate, tool size, and electrical power.
4) Based on the above experiment we have to obtain optimum input variables for minimum surface roughness condition.

III. WORKING PRINCIPLE

When electric current is passed through an electrically resistive metal wire, the heat is generated in the wire resulting increase in temperature.This is known as the joule heating effect and is defined by equation (3.1).

$$Q = I^2 R \quad (3.1)$$

Where the units of Q, I and R, are power (Watt), current (Ampere) and resistance (ohm) respectively.

As the wire is a linear heat source it will be meaningful to use linear heat source by dividing volumetric heat by length of the wire as shown in equation (3.2).

$$Q_L = \frac{Q}{L_e} \quad (3.2)$$

Where Le represents the active length of hot wire taking part in cutting operation. In order to consider the influence of the heat input and the cutting speed together, the effective heat input is described as shown in Eq 3.3:

$$Q_{eff} = \frac{Q_L}{V_C} \quad (3.3)$$

Where Vc is the cutting velocity in m/s and Q_{eff} has the units of W·s/m² or J/m². Physically this value represents the amount ofelectrical/thermal energy used to create a unit area of cut surface. It is a very useful parameter asit allows a wide range of cutting data to be presented on a single graph. Ahn et al used this parameter Q_{eff} toobserve energy input [3,4, 5].

For thin foam sheet slicing the temperature of wire is assumed to be constant but this is not true when slicing a thick block of foam. Temperature of the wire cools down as wire plunges into the foam block [6].

Primarily three cutting stages were identified in hot wire foam cutting [7] as shown in figure 1.

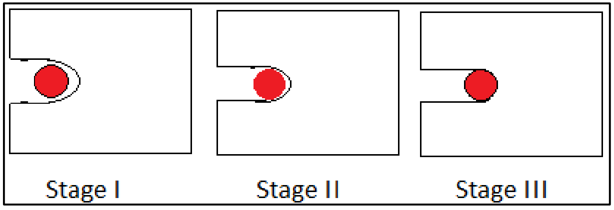

Fig. 1: Three cutting stages with a hot-wire

Stage I is dominated by thermal process where material removal is due to vaporization of the foam due to high temperature of the wire. Stage III is dominated by mechanical process where wire and foam are in close contact with each other and material removal takes place as if wire cuts over the foam. Stage II is the transitional phase between stage I and stage III where the cutting mechanisms of stage I changes into the cutting mechanisms of stage III. In stage II material removal takes place due to the combined action of thermal and mechanical process. There is no mechanical force on the wire. Mechanism in stage I, II and III are called thermal cutting, thermo-mechanical cutting & mechanical cutting respectively [7]. These three zones primarily depend on input variables wire diameter, feed rate and supply voltage.

IV. MATHEMATICAL MODELING

A. *Static Condition*

When electric current is passed through the static nichrome wire in open air after certain time steady state is reached temperature stands constant.

$$E_i - E_o = \frac{d}{dt} m c_p (T - T_o)$$

Where E_i&E_o are the energy input and energy loss through the wire. E_i is the joule heat as shown above eqn(3.1). Energy loss takes place only due to radiation and convection.

At steady state RHS is zero.

$$I^2 R - \sigma\epsilon A(T^4 - T_o^4) - hA(T - T_o) = 0$$

$$\frac{V^2}{R} - \sigma\epsilon\pi dl(T^4 - T_o^4) - h\pi dl(T - T_o) = 0$$

$$\frac{V^2}{R} = \sigma\epsilon\pi dl(T^4 - T_o^4) + h\pi dl(T - T_o)$$

Where V: voltage across the wire; R: resistance of nichrome at that temp.; σ: emissivity of nichrome; ε: Stefan-Boltzmann constant: d: diameter of nichrome wire; l: length of nichrome wire; T:steady state temp. ofnichrome wire; T_o : Room temperature; h: heat transfer coefficient of room air;

For 24WG wire d=0.00051m; V:20v; R:8.184Ω

$$\frac{20 \times 20}{8.184} = 5.67 \times 10^{-8} \times 0.75 \times \pi \times 0.00051 \times 1(T^4 - 293^4) + 25 \times \pi \times 0.00051 \times 1(T - 293)$$

$$6.813 \times 10^{-11} T^4 + 0.04\,T = 48.87 + 0.5 + 11.73 = 61.1$$

By trial and error method we get T= 804 K = 531°C

B. *Dynamic Condition:*

When the hot nichrome wire is driven into the job(thermocol)continuously the heat in the wire will be dissipated to thermocol to vaporize it. The balance heat will remain in the nichrome wire to maintain its temperature.

The amount of heat required to vaporize the thermocol is given as

$$\Delta H_g = \int_{T_a}^{T_m} C_{p,s}\, dT + \Delta H_m + \int_{T_m}^{T_v} C_{p,l}\, dT + \Delta H_v$$

where ΔH_m and ΔH_v are the latent heat of the melting and vapourization at respective melting point and vaporization point in MJ/kg, $C_{p,s}$ and $C_{p,l}$ are the specific heats in solid and molten state in MJ/kgK. From thermal properties of polymers handbook it has been found that ΔH_g for EPS is 1.3MJ/kg.

The cutting arrangement is shown in the fig.2 below.

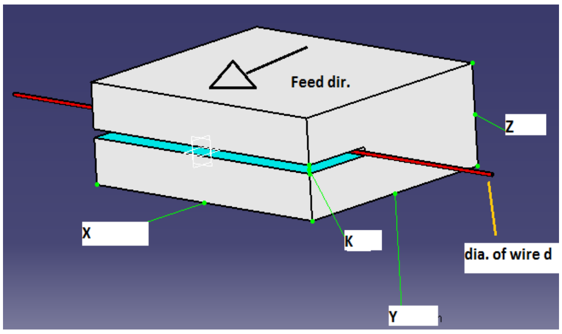

Fig. 2: Cutting arrangement with hot-wire

The temperature of the hot nichrome wire was measured at the middle of the thermocol block where the wire plunges into the block by hooking a thermocouple over the hot nichrome wire as shown in the figure 3.

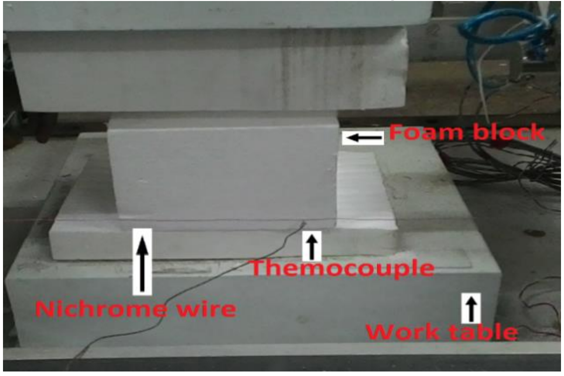

Fig. 3: Arrangement of thermocouple

Following assumptions are made in the study.

C. *Assumptions:*

Heat loss by the portion of the nichrome wire which is engaged in slicing operation is entirely absorbed by thermocol.

Temperature of the adjacent nichrome wire which does not take part in the slicing operation remained unaffected.

Heat loss by nichrome wire portion which goes inside the thermocol block for slicing will be entirely absorbed the thermocol. Heat required to vaporize the thermocol is the product of mass removed and total heat of vaporization as stated above. Mass removed can be obtained by multiplying the volume removed and its density or by measuring the difference in mass before slicing and after slicing.

Total heat required to vaporize thermocol

$$H_t = \Delta H_g \times \Delta m$$

For 24WG 400mm/min feed and for a particular thermocol block, $\Delta m = 3.86 \times 10^{-5}$ kg.

$$H_t = 50.18J$$

Heat generated in the nichrome wire due to joule heating for that particular condition is 145.53J

Therefore, net heat remained in the wire

$$\Delta H = 145.53 - 50.18 = 95.35J$$

The same heat will be used to raise the temperature of the nichrome wire.

$mC_p\Delta T = 95.35$

$$\Delta T = 233^oC$$

Final temperature of wire, $T_f = 253^oC$

In the same way the temperatures at various input conditions are estimated.

V. EXPERIMENTAL WORK DONE

The experiments fall into two categories: cutting trials aimed at validating the mathematical model of the nichrome wire temperature and second to find out optimum input conditions for minimum surface roughness.

A. *Experimental Set-Up*

The experimental set-up is shown in the fig. 4below. It is comprised of a 3 axes CNC machine, Fanuc O-i series controller, Braking devices, four vertical guide columns, carriage, hot-wire cutting device, EPS sample and foam sample holding fixture.

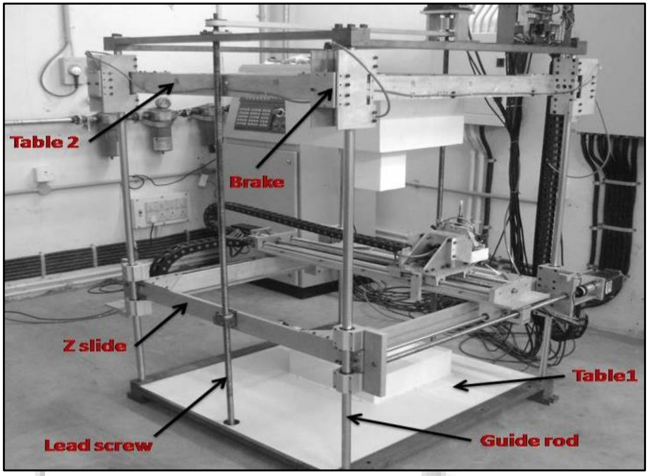

Fig. 4: Experiment Set-up

B. *Materials*

The work material used in the cutting trials is Expanded polystyrene (EPS) foam, commercially called thermocol. Chemical formula is $(C_8H_8)_n$. EPS foams are inexpensive and are widely available.

The tool material is nichrome, which is an alloy of nickel and chromium. It contains 80% nickel and 20% chromium. This tool material is also called as electrical resistance wire. Work piece is located at the centre of the machine set up and the carriage is given motions. A power supply is used 14V-25V DC.

VI. EXPERIMENTAL PROCEDURE

The cutting trials consisted of over 100 individual cuts from which a significant number of measurements were made. The general cutting procedure for all the cutting tests was as follows:

1) A thermocol block was held on the cutting table, wire was positioned suitably with the help of controller.
2) Power was supplied to the wire and voltage was adjusted and fixed at certain value with the help of potentiometer connected at the Fanuc controller.
3) The temperature of the wire was continuously monitored with the help of thermocouple connected to the nichrome wire. When the temperature of the nichrome wire got stabilised cutting motion was started at a predetermined feed rate as shown in the fig. 6 below.

Fig. 5: Cutting operation

4) After finishing the cut keeping the voltage same feed was changed to next value. The process was repeated till wire started bowing due to mechanical contact with polystyrene foam.
5) Thereafter, voltage was changed. In the experiment different voltages were selected in the range of 14V-25V.
6) Steps (b) to (e) were then repeated changing the cutting wire of different gauge. In the experiment 3 different wire gauges were used 24WG, 28WG, 34WG.

VII. RESULTS AND DISCUSSION

A. *Temperature of Nichrome Wire*

The temperature of the wire was continuously monitored with the help of thermocouple connected to the nichrome wire. Temperature of nichrome wire in open air before it plunges into foam is shown in the fig. 5 for three different sizes of wire (24 WG, 28WG, 34WG). The figure also shows the estimated values of temperature of those three sizes wire at various supply voltage.

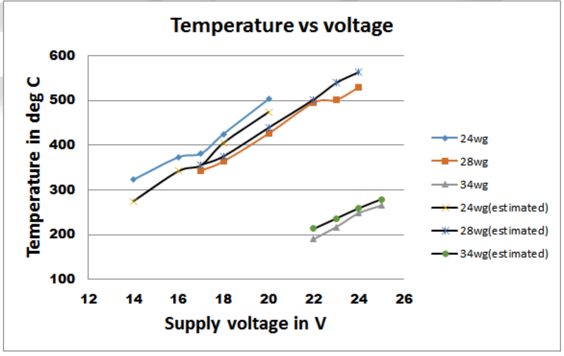

Fig. 6: Temperature of nichrome wire in open air

When the slicing started by the hot wire temperature was dropped initially but after some time steady state is reached and temperature of the wire becomes almost stable for constant feed rate. Fig. 7 shows temperature of 24WG wire during slicing at various feed rate.

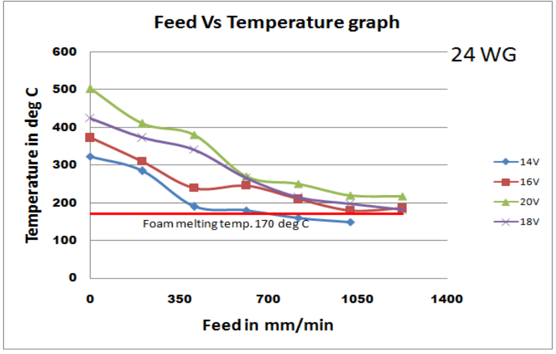

Fig. 7: Temperature of 24WG wire at different voltages

The steady state temperature for other two size of wires (28WG & 34WG) during slicing are shown in fig. 8 & 9 respectively. Horizontal lines in fig. 7, 8 & 9 are representing the melting temperature of foam.

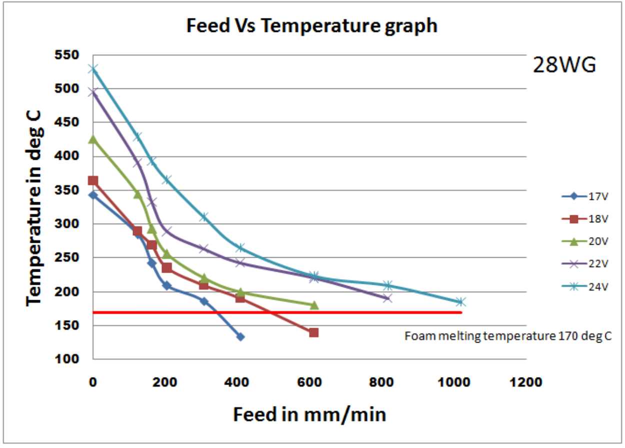

Fig. 8: Temperature of 28WG wire at different voltages

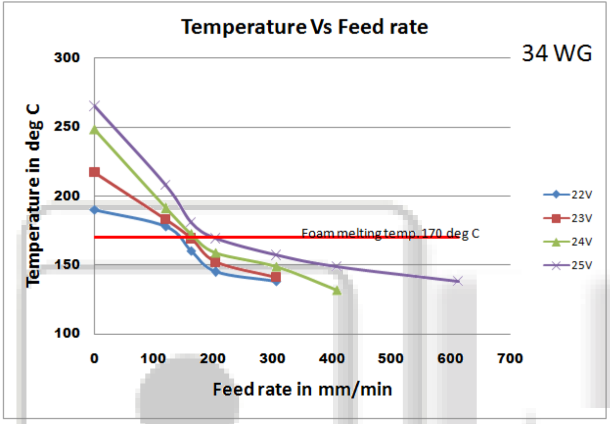

Fig. 9: Temperature of 34 WG wire at different voltages

B. *Surface Roughness Dynamics*

A contact type profilometer "MITUTOYO" is used to measure the surface quality. The stylus of the profilometer is moved over a distance of 15 mm at 3 different orientation at 120°apart, then average value was taken to get the surface quality of the foam. Same values are used to plot the graph between surface roughness and feedrate. Surface roughness was measured for the sliced sample of the foam at four different voltages each for three nichrome wire sizes (24WG, 28WG, 34WG). The results are shown in the figures 10, 11, 12 & 13 below.

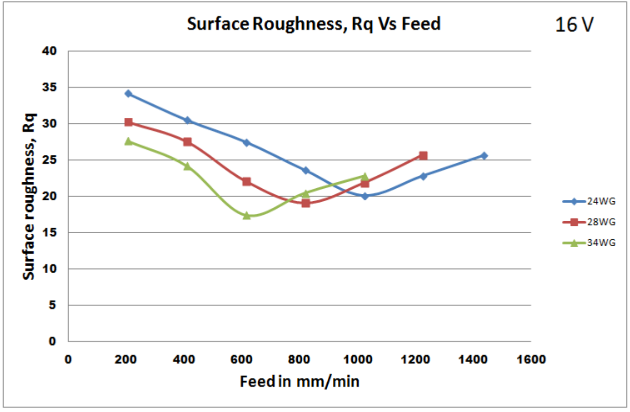

Fig. 10: Surface roughness Vs feed for 16 V

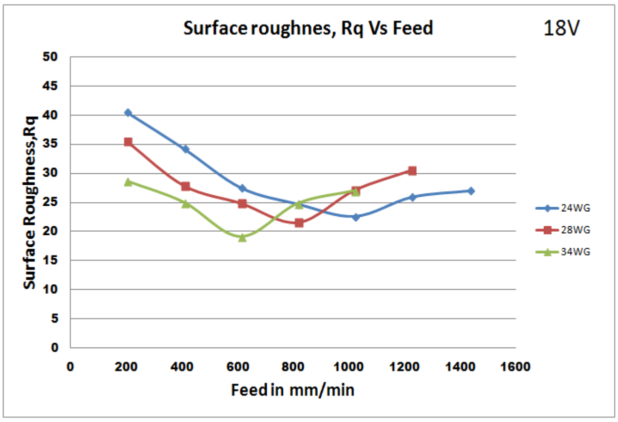

Fig. 11: Surface roughness Vs feed for 18V

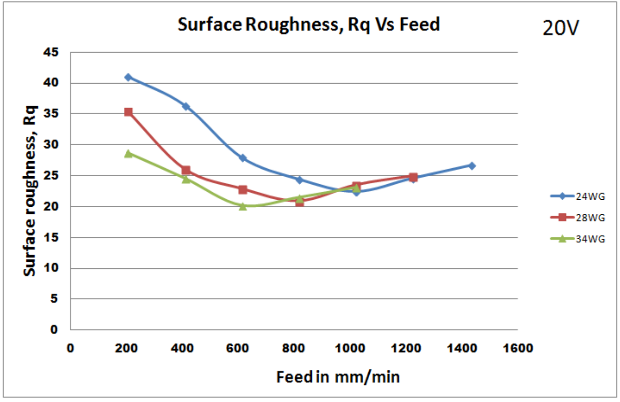

Fig. 12: Surface roughness Vs feed for 20V

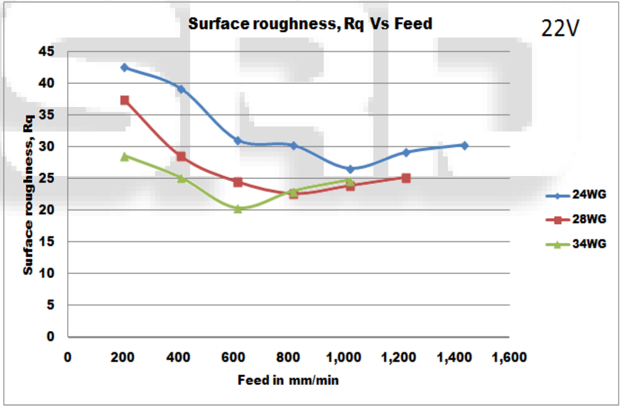

Fig. 13: Surface roughness Vs feed for 22V

C. *Discussion*

From the surface roughness graphs it is evident that at the beginning of the graph the surface is quite rough when the feed rate is very low but with increase of feed rate surface quality improves i.e surface roughness value reduces. This improvement of surface quality continuesup to a certain value of feed rate then surface quality starts deteriorating and value of surface roughness increases. The value of this critical feed rate depends upon the wire size and supply voltage. When the wire size increases at a particular voltage minimum surface roughness occurs at a higher feed rate and that minimum surface roughness value increases for larger diameter wire. On the other hand when the supply voltage increases at a particular wire size minimum surface roughness value increases. This can be explained with the fact that at low feed rate thermal ablation takes place and foam melts in the vicinity of the hot wire due to radiation heat of the wire but as soon as wire passes the melting zone the molten foam solidifies and giving a rough surface. With higher feed rate material removal is due to combination of thermal and mechanical action due to less steady state temperature of the nichrome wire foam. The melting zone of foam is also limited and before complete melting of the foam hot wire passes the melting zone. In this zone we get better surface. But with further increase in the feed rate slicing mechanism is completely mechanical which again gives rise to rough surface. In this process wire tears the foam due to physical contact.

VIII. CONCLUSION

From the above graphs, the optimum cutting conditions for minimum surface roughness can easily be observed. Minimum surface roughness is based on wire size, supply voltage, feed rate. Higher the size of the wires higher the value of feed rate at which minimum surface roughness is obtained. For wire size 24WG optimum feed rate is 1000 mm/min, for 28WG wire size optimum feed rate is 800mm/min and for 34WG wire size optimum feed rate 600mm/min. The corresponding optimum supply voltage and steady state temperature of the wire are shown in the table 1.

Wire gauge	Feed rate (mm/min)	Voltage (V)	Steady state temp.(oC)	Surface roughness (Ra) in µm
24WG	1000	16	190	20
28WG	800	20	190	21
34WG	600	16	170	17

Table 1: Optimum slicing conditions

IX. FUTURE SCOPE

The existing machine has 3 linear motions in x,y,z directions and no surface of revolution can be generated with this machine. This limits the application of this machine for manufacturing complicated parts.Rotational motion of the table can be considered for creating surface of revolution and to validate the result in rotational motion.Moreover, if data acquisition system (DAS) is incorporated in the system which can continuously monitor the temperature of the hot wire then it would be easier to control the temperature of the hot wire by changing the voltage.

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