Numerical Analysis of Grinding Process Parameters for End Profiling of Needle Roller Bearing with SAE52100

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Abstract— High temperature rise in grinding process can cause burning of the needle. The primary objective of this paper was to develop an improved theoretical thermal model which would predict the grinding temperatures, the energy partition to the needle and heat flux distribution within the grinding zone. In all cases, the maximum grinding zone temperature rise was less than 120°C.The energy partition to the needle was found to be 6.2%.Such low energy partition is consistent with thermal model which takes into account conduction to the needle, conduction to the abrasive grains, and cooling of the needle by the fluid at grinding zone. The secondary objective is to optimize temperature rise between wheel and needle contact zone in a cylindrical grinding process so as to reduce thermal damage and thereby grinding burn.

Key words: Grinding, Thermal Damage, Needle Burn, Optimization, Taguchi’s Method, Temperature

I. INTRODUCTION

Grinding is an accurate machining process suitable for finishing materials of high hardness. It requires a large amount of energy per unit volume of material removal compared to other metal cutting process [1].During material removal, energy expended by the process is converted into heat and the heat becomes concentrated in the grinding zone. This can lead to high temperature and various types of thermal damage to the needle, such as burning, softening (tempering) of the surface layer with possible rehardening and embrittlement, unfavorable residual tensile stresses, and cracks [2]. Thermal damage to the workpiece is one of the main constraints on the production rates that can be achieved in grinding. For grinding of bearing steels, it has been shown that workpiece burn occurs at a critical temperature. Therefore, workpiece burn can be avoided if the workpiece temperature is maintained below this critical value. To actively control workpiece burn, a relationship is needed between the temperature rise and grinding conditions, including such factors as abrasive type, fluid application condition, and operating parameters (for example, wheel speed, work speed, coolant flow rate). The workpiece temperature can be calculated from the measured power using moving heat source theory or a finite element method, provided that the heat flux distribution at the grinding zone and the energy partition to the workpiece are known. [3].

Heating of the workpiece in the grinding process, results in a positive heat flux at the grinding zone. The convective cooling by the grinding fluids, whereas results in a negative heat flux. The present investigation is concerned with the optimization of rise in surface temperature through Taguchi’s parameter design technique.

Most of the thermal analyses in the grinding process are based on the moving heat source theory. According to this theory, it is necessary to know the fraction of energy conducted as heat to the workpiece in order to estimate the workpiece temperature. This fraction of energy plays a key role in predicting the rise in workpiece temperature, the energy partition to the workpiece, heat flux distribution within the grinding zone and understanding the related thermal phenomena, like grain contact length, grain contact time, grain depth of cut, etc., within the grinding zone [4]

II. THERMAL MODEL

A. *Theoretical Energy Partition:*

Heat generated in the contact area between the wheel and the workpiece is the main cause of deterioration in the metallurgical properties of the workpiece, surface finish, dimensional accuracy, and wheel life. When grinding with Al2O3 wheel about 80% of the total energy ends up in the workpiece itself and 20% of total energy to abrasive particles in wheel and negligible energy to chips [5].

Rowe et al. [6]. determined the thermal properties of conventional type of grinding wheels by steady state experiments. The contact zone models consider the partitioning of energy over the whole grinding contact zone. The wheel bulk property model assumes that the work-piece and the grinding wheel are subjected to sliding heat source.

Rowe et al. [7]. Proposed a grain model in which the partition ratios (partition ratio is defined as a proportion of heat entering into the workpiece to the total heat developed) were considered without taking into account the energy convected away by the chips and coolant.

Partition ratio (ε): The partition ratio is the proportion of the heat entering the needle to the total heat generated.

$$\varepsilon = \frac{Q_w}{Q_t} \qquad (1)$$

Where,

Q_w Amount of heat entering the needle in W/mm,
Q_t Total heat produced in W/mm

For a square law distribution the partition ratio is given by

$$\varepsilon = 0.83.b.\sqrt{(k\rho c)_w}.\sqrt{V_w}.\sqrt{L_e.\theta_m} / Q_t \qquad (2)$$

Where,

b	Grinding wheel width(m)
$\sqrt{(k\rho c)_w}$	Thermal contact coefficient for needle ($Jm^{-2}S^{-0.5}K^{-1}$)
V_w	Velocity of needle (m/s)
Θ_m	Background temperature (°C)

Justification for using square law distribution is based on the assumption that the heat distribution is uniform along the contact area and the flow is radially inward to the needle [4]. Theoretical models are required to predict the partition ratio and needle temperature. First, in grain contact zone model proposed by Rowe and Black [7]. by considering the partitioning of energy over the whole girding contact, the partition ratio for various materials are found.

$$1/\varepsilon_{th} = 1 + \left\{ \sqrt{V_s/V_w} \cdot \left[\sqrt{(k\rho c)_s} \Big/ \sqrt{(k\rho c)_w} \right] \right\} \tag{3}$$

Where,

V_s Velocity of grinding wheel (m/s)

$\sqrt{(k\rho c)_s}$ Wheel bulk thermal co-efficient ($Jm^{-2}S^{-0.5}K^{-1}$)

ε_{th} Theoretical partition ratio where energy convected by the chips and coolant is ignored.

The bulk thermal co-efficient for alumina wheel is found by separate measurements of k_s, ρ_s and c_s for samples of vitrified abrasive by Lee's conductivity apparatus, gravimetric and calorimetric methods [4]. It was found that for alumina wheel, the bulk thermal coefficient is,

$$\sqrt{(k\rho c)_s} = 0.20\, kJm^{-2} S^{-0.5} K^{-1}$$

Thus, bulk thermal coefficient for SAE52100 needle material used in this research is found by using their physical properties.

$$\sqrt{(k\rho c)_w} = 12.60\, kJm^{-2} S^{-0.5} K^{-1}$$

Using the Rowe's grain contact zone model the partition ratio SAE52100 needle material is found using the following needle and wheel conditions.

V_w	velocity of Needle	$2.63 \times 10^{-3}\, m/s$
V_s	Surface velocity of grinding wheel	$25.65 m/s$
d_w	Diameter of Needle	3.148mm
d_s	Diameter of grinding wheel	350mm
$(k\rho c)_f$	Thermal contact coefficient for fluid	$2.72 \times 10^{6}\, J^{2} m^{-4} k^{-2} S^{-1}$
$(k\rho c)_g$	Thermal contact coefficient for grains	$0.14 \times 10^{9}\, J^{2} m^{-4} k^{-2} S^{-1}$
α_g	Thermal diffusivity of grains	$1.20 \times 10^{-5}\, m/s$

Table 1: Needle and wheel conditions

$$1/\varepsilon_{th} = 1 + \left\{ \sqrt{V_s/V_w} \cdot \left[\sqrt{(k\rho c)_s} \Big/ \sqrt{(k\rho c)_w} \right] \right\}.$$

$$1/\varepsilon_{th} = 1 + \left\{ \sqrt{0.35/0.00263} \cdot \left[0.20/12.60 \right] \right\}$$

$$\varepsilon_{th} = 0.389.$$

B. *Experimental Energy Partition:*

The theoretical energy partition ratio does not consider the portion of energy convected by chips, e_{cc}, and coolant, e_{cf}. In the present work they have also been included, and then the partition ratio is reduced to

$$\varepsilon = \varepsilon_{th} \left[1 - \left\{ (e_{cc} + e_{cf}) / e_c \right\} \right] \tag{4}$$

Where,

e_c – Specific chip energy (J/mm^3)

According to Howes and Neailey [4]., typical value of e_{cc} is 6 J/mm3 and e_{cf} tends to be very small where fluid boiling occurs [e_{cf}=0]. Water based fluid undergo film boiling at a temperature around 120°C. Once film boiling occurs, the grinding fluid becomes ineffective as a coolant, and conditions are essentially equivalent to dry grinding. Assuming that needle burn occurs somewhere between 723°C (the eutectoid temperature) and 800°C (for formation of untempered martensite), and the bulk needle temperature is 20°C or greater, then θ_{burn} is somewhere around 700°C [2]. Thus, considering the allowance the original partition ratio can be given by

$$\varepsilon_{dry} = \varepsilon_{th} \left[1 - (6/e_c) \right] \tag{5}$$

The effect of chip becomes increasingly significant at lower specific energies and according to Rowe and Black, the specific energy of the chip is assumed to be e_c=40 J/mm3. Thus, the partition ratio for the workpiece material is found as.

$$\varepsilon_{dry} = 0.389 \left[1 - (6/40) \right]$$

$$\varepsilon_{dry} = 0.33 \tag{6}$$

1) Determination of Grain Depth of Cut, Grain Contact Length, and Grain Contact Time With The Chip:

Using the grain contact model developed by Rowe and Black, the solution for partitioning of heat between the wheel and the workpiece is

$$\varepsilon_{dry} = 1 \Big/ \left\{ 1 + \left(k_{ge} \big/ \sqrt{r_0} V_s \right) \left[1 \big/ \sqrt{(k\rho c)_w} \right] \right\} \tag{7}$$

$$0.33 = 1 \Big/ \left\{ 1 + \left(35 \big/ \sqrt{r_0}\, 25.65 \right) \left[1 \big/ (12.60 \times 10^{3}) \right] \right\}$$

$$\sqrt{r_0} = 53.2\, \mu m$$

$$L_e = \sqrt{r_0}\, d_e$$

$$where,$$

$$d_e = \left[d_s . d_w \big/ (d + d_w \right]$$

$$d_e = 3.12\, mm$$

$$L_e = 0.167\, \mu m$$

$$t = \frac{L_e}{V_s}$$

$$t = 0.00652\, \mu s$$

Where,
K_{ge} - Thermal conductivity of the grinding wheel (W/mK) for alumina wheel (k_{ge}=35W/mK)
r_0 - Grain depth of cut (µm)
L_e - Optimal grain contact length
t - Grain contact time

C. Heat Transfer Analysis:

The maximum workpiece surface temperature is a function of the grinding energy and the various grinding parameters. Heat transfer to the needle, wheel, and coolant was included. Heat transfer within the workpiece was considered first. It is assumed that the workpiece surface was exposed to a uniform heat flux, due to the distributed action of all the grains [2]. And by the fluids and triangular band source of heat at the grinding zone moving along the surface of needle as shown in Fig 1. [8].

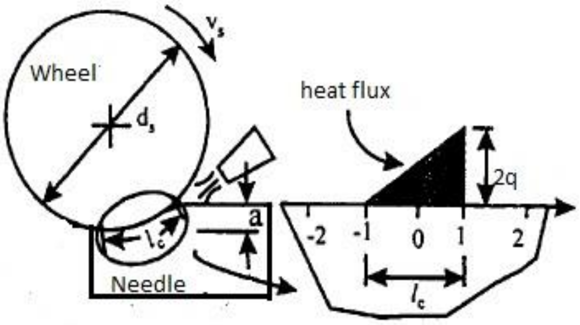

Fig. 1: Illustration of grinding and thermal model.

1) Calibration of Heat Entering Into the Workpiece:

From the tsquare law distribution

$$\varepsilon = Q_w / Q_t = 0.83 . b . \sqrt{(k\rho c)_w} \sqrt{V_w} \sqrt{L_e} \theta_m / Q_t$$

therefore ,

$$Q_w = 0.83 . b . \sqrt{(k\rho c)_w} \sqrt{V_w} \sqrt{L_e} \theta_m$$

$$Q_w = 0.2805\, W / mm$$

2) Total Average Heat Flux:

$$q = \frac{P}{l_c b}$$

$$q = \frac{373}{2.5 \times 10^{-3} \times 0.04} = 3.73\, w / mm^2$$

Where
q- Total average heat flux (W/mm^2)
P- Grinding power (W)
L_c- Contact length

3) Average Heat Flux to The Needle At The Grinding Zone

$$q_w = \varepsilon q$$

$$q_w = 0.062 \times 3.73 = 0.23\, w / mm^2$$

4) Critical Temperature for The Avoidance Of Thermal Damage:

In order to predict thermal damage it is necessary to know the critical temperature at which damage occurs. The use of coolant introduces an additional heat sink into the grinding process. Coolant is also important because it reduces friction in the grinding process so that lower energy is required to grind.

Another approach for analyzing the energy partition is the single grain model. This model also includes the effects of heat transfer to the abrasive grains, fluid, and needle by considering a single grain surrounded by fluid interacting with the needle as shown in Fig 2. [8].

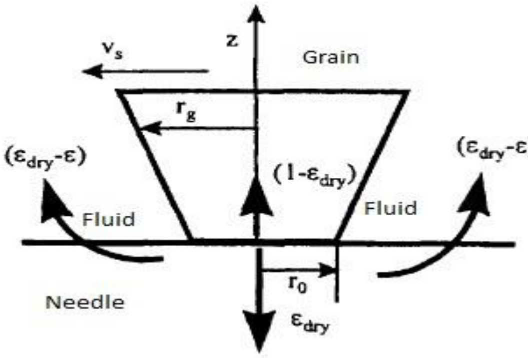

Fig. 2: Single grain energy partition model

Each single active grain is modeled as a truncated cone moving along the needle surface at the wheel speed V_s with all of the grinding energy uniformly dissipated as heat at the grain-needle interface of area A_0. At this interface, part of the energy ε_{dry} initially conducted to the needle and the remainder to the abrasive grain. Cooling by the fluid is then taken into account by considering the temperature at the fluid-needle interface within the grinding zone. For this model, the maximum temperature rise at the grain-needle interface is [8].

$$\theta_{\max\ g} = 1.128 \frac{(1-\varepsilon_{dry})q}{\sqrt{(k\rho c)_g}} \sqrt{\frac{l_c}{V_s}} \frac{1}{f(\varsigma)A} \qquad (8)$$

$$f(\varsigma) = \frac{2}{\sqrt{\Pi}} \frac{\varsigma}{1-\exp(\varsigma^2) erfc(\varsigma)} \qquad (9)$$

Where,

$$\varsigma = \sqrt{\frac{l_c \gamma^2 \Pi \alpha_g}{A_0 V_s}} \qquad (10)$$

Γ is a geometric grain shape factor defined as:

$$\gamma = \frac{dr_g}{dz}$$

And r_g is the grain radius. Grinding fluid entering the wheel pores is quickly accelerated and can be considered to be moving at the wheel speed within the grinding zone [9]. At its interface with the needle, the maximum temperature rise of the fluid can be written as [8].

$$\theta_{\max\ f} = 1.06 \frac{(\varepsilon_{dry}-\varepsilon)}{\sqrt{(k\rho c)_f}} \sqrt{\frac{l_c}{V_s}} \frac{1}{(1-A)} \qquad (11)$$

Where ε is the fraction of the total energy not removed by the fluid (energy partition) and subscript *f* refers to the fluid. The maximum workpiece temperature rise can be expressed as:

$$\theta_{\max} = 1.06 \frac{\varepsilon q}{\sqrt{(k\rho c)_w}} \sqrt{\frac{l_c}{V_w}} \qquad (12)$$

If the maximum temperature at the workpiece-fluid interface is the same as at the workpiece-grain interface (θ_{max}=θ_{maxf}=θ_{maxg}), the overall energy partition to the workpiece is finally obtained by combining Equations (8), (11), (12):

$$\varepsilon = \frac{1}{1 + \Omega\sqrt{\frac{V_s}{V_w}}} \qquad (13)$$

Where,

$$\Omega = 0.94\sqrt{\frac{(k\rho c)_g}{(k\rho c)_w}}Af(\varsigma) + \sqrt{\frac{(k\rho c)_f}{(k\rho c)_w}}(1 - A) \qquad (14)$$

On solving equations (8), (9), (10), (13), (14)
ζ= 1.7146, erfc(ζ)= 0.015593, f(ζ)= 2.743, θ_{maxg}= 78.19°C, Ω= 0.153, ε= 6.2%

This single grain energy partition model can be used to account for the differences in energy partition to the needle under various grinding and fluid application conditions. For regular grinding with conventional aluminum oxide wheels and water-based fluids, the grinding zone temperature was 78.19°C which is below burnout limit of 130° C, so cooling by the fluid was effective at the grinding zone.

III. RESULT AND DISCUSSION

A. Optimization of Grinding Zone Temperature and Needle Hardness:

In order to optimize the temperature developed in the grain contact zone, experiments are carried out in a high precision grinding(Chamfering) machine as per the L9 orthogonal array and the methodology is presented below. Theoretically, the amount of heat generation and wheel needle contact zone temperature are calculated and the results are reported.

ANOVA analysis is carried out to determine the influence of main factors and to determine the percentage contribution of each factor.

S. No	Parameter	Unit	Level		
			Low	Medium	High
1	Wheel speed	m/s	30.15	30.63	32.98
2	Needle speed	Rpm	16	18	20
3	Coolant flow Rate	Lpm	9.36	12.5	14.5

Table 2: Details of parameters and their levels used in the experimentation

ANOVA analysis has given the percentage contribution of wheel speed (32.92%), needle speed (6%), coolant flow rate (46.94%), and wheel speed (16%) on the grinding zone temperature and wheel speed (3.76%), needle speed (2.72%), coolant flow rate (53.52%) on needle hardness. It clearly shows that the coolant flow rate was having more influence on the grinding zone temperature and needle hardness obtainable compared to other grinding parameters.

ANOVA analysis is extended to determine the influence of main factors on the wheel-needle contact zone temperature rise and needle hardness. The effects of main factors on temperature and surface hardness are given in Fig 3. and Fig 4. For SAE52100 needle material.

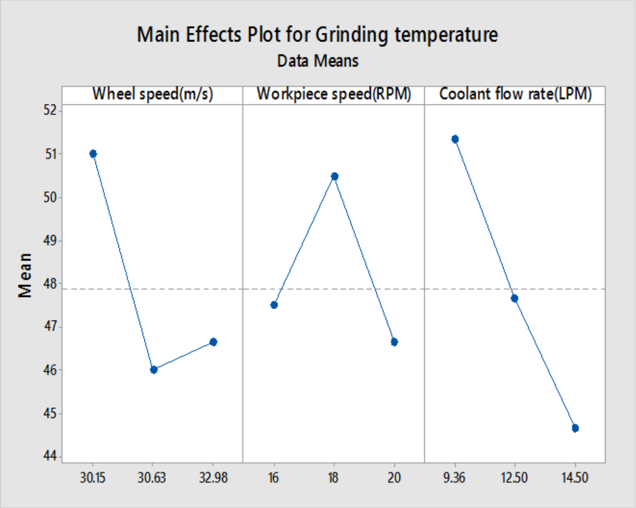

Fig. 3: Main Effect plot for grinding zone temperature

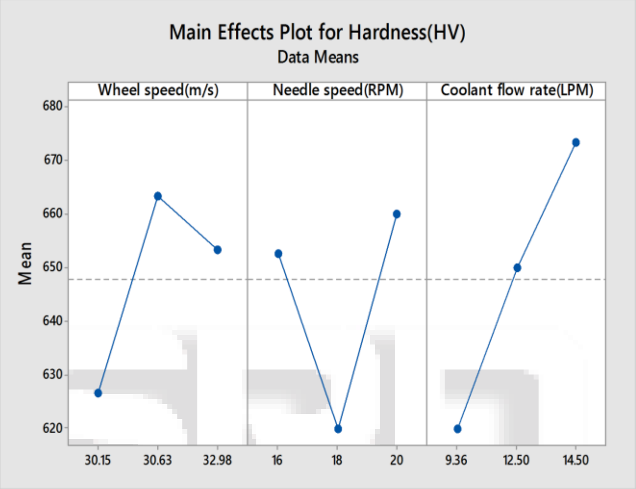

Fig. 4: Main Effect plot for Needle hardness

The optimum grinding conditions obtained in the present work for various requirements are listed below;

1) *Low grinding zone temperature*

Wheel speed-30.63m/s, Needle speed- 20rpm, Coolant flow rate- 14.50lpm

2) *High Needle Hardness*

Wheel speed- 30.63m/s, Needle speed- 20rpm, Coolant flow rate- 14.50lpm

The confirmation test was carried out and it was validated. The minimum temperature recorded by using the above optimum parameters was 40°C and the maximum needle hardness recorded was 690 HV.

B. Regression Analysis:

Regression analysis gives the functional relationship between input parameters and output response.

Regression equation for grinding zone temperature as a function of wheel speed, needle speed, and coolant flow rate is:

Grinding temperature = 98.8-0.921 Wheel speed (m/s)-0.341 needle speed (RPM)-1.326 Coolant flow rate (LPM)

Regression equation for Needle hardness as a function of wheel speed, needle speed, and coolant flow rate is:

Hardness (HV) = 317+4.79 Wheel speed (m/s) +2.91 Needle speed (RPM) +10.65 Coolant flow rate (LPM)

IV. CONCLUSION

Energy partition to the needle is calculated to determine the maximum needle temperature rise at the grinding zone. The maximum needle temperature rise is below the fluid film boiling temperature so cooling by fluid is effective at the grinding zone. The optimum temperature is compatible with moving heat source theory for triangular heat flux distribution at the grinding zone. By performing ANOVA it is observed that the coolant flow rate has the highest statistical influence on the grinding zone temperature as well as on needle hardness.

It is concluded from result that maintaining coolant flow rate at high level, wheel speed at medium level and needle speed at high level, the temperature rise at the grinding zone is below burn out limit and hardness of needle is near to the required hardness.

REFERENCES

[1] W B Rowe, S C Black, B Milla, H S Qi, “Analysis of grinding temperatures by energy partitioning”, Journal of Engineering Manufacture, Vol 210, pp. 579-588, 1996.
[2] Lavine, A.S., Malkin, S., Jen, T.C., “Thermal Aspects of Grinding with CBN Abrasives”, Annals of the CIRP, 38/1, pp. 557-560, 1989.
[3] Guo, C., Malkin, S., “Energy Partition and Cooling During Grinding”, Journal of Manufacturing Processes, 2, pp. 151-157, 2000.
[4] N. Alagumurthi & K. Palaniradja & V. Soundararajan , Heat generation and heat transfer in cylindrical grinding process - a numerical study, Int J Adv Manuf Technol 34, pp. 474–482 , 2007.
[5] Kohli, S., Guo, C., Malkin, S., “Energy Partition to the Workpiece for Grinding with Aluminum Oxide and CBN Abrasive Wheels”, ASME Journal of Engineering for Industry, 117, pp. 160-168, 1993.
[6] Rowe, W. B., Petit, J. A., Boyle, A., Moruzzi, J. L., “Avoidance of Thermal Damage in Grinding and Prediction of Damage Threshold”, Annals of the CIRP, 37/1, pp. 327-330, 1988.
[7] Rowe, B. W., Morgan, M. N., Black, S. C. E., Mills, B., “A Simplified Approach to Control of Thermal Damage in Grinding”, Annals of the CIRP, 45/1, pp. 299-302, 1996.
[8] Guo, C. Wu, Y, Varghese, V., Malkin, S., “Temperature and Energy Partition for Grinding with Vitrified CBN Wheels”, Annals of the CIRP, 48/1, pp. 247-250, 1999.
[9] S. Malkin, C. Guo., “Thermal analysis of Grinding”, Annals of the CIRP, Vol. 56/2, pp. 760-782, 2007