Analysis of reverse heat transfer for conventional and optimized lubri-cooling methods during tangential surface grinding of ABNT 1020 steel

Abstract

A numerical thermal model was developed to evaluate the heat flux which is conducted to a rectangular workpiece of steel plate ABNT 1020, thus making it possible to compute the maximum temperature in the grinding surface, taking into account the rectangular distribution of heat flux, the thermal properties of the grinding wheel conventional Al₂O₃, the piece to be machined and the lubri-refrigerating fluid. The finite volume method was employed for the discretization of the direct thermal problem from the heat diffusion equation associated with the two-dimensional problem of heat conduction in transient regime. The inverse thermal problem was solved by the Golden Section technique. The thermal flux, when compared to the conventional technique of method of application fluid, was reduced by 84.0% in the practices performed with cutting depth of 30µm, at 74.0% in practices with cutting depth of 45µm and 61.2% in the aggressive practices of 60µm, thus demonstrating the applicability of the optimized method for fluid application.

keywords: inverse heat transfer, thermal damage on the surface grinding, optimized method of fluid application.
1. Introduction

A considerable number of studies using analytical and experimental methods in heat transfer in the grinding process are based on Jaeger, J. C. (1942) pioneer work. The application of Jaeger’s moving heat source solutions to heat transfer problems in grinding was first proposed by Outwater and Shaw (1952), whereby they consider a constant intensity heat source moving over the surface of a semi-infinite solid, which increases workpiece temperature. The authors assumed that all the grinding energy was directed to the formation of the chip. According to Guo and Malkin (1995), the heat generated in the grinding zone is dissipated through the workpiece, the grinding wheel, the generated chips and the cutting fluid, wherein the partition of energy flowing through each of these elements has been the object study and, in particular, that which flows through the piece, because the increase in temperature on its surface is a result of higher energy partition for it. According to Malkin and Guo, (2008), the grinding process, compared to other machining processes, involves high specific energy. The major fraction of this energy is changed into heat which produces a harmful effect on surface quality as well as tool wear.

1.1 Energy partitioning

According to Zhang, L. (2012), there are four regions where mechanical energy in the process is transformed into heat. Friction at flank of worn grains and plastic deformation of the machined material generate most of the heat, which is dissipated by three process elements: the abrasive grain, chip and cooling fluid. The heat flux conducted to workpiece, \( q_w \), is only part of the total heat flux. Since the total machining power is represented as the total heat flux according to Equation (1). Therefore, we may write:

\[
q_t = \frac{P}{I_p b} = \frac{F v_s}{\sqrt{ad} b} = q_w + q_s + q_{ch} + q_f
\]

(1)

Wherein: \( q_w \) is the input heat flux in workpiece at the contact zone; \( q_s \) is the dissipated heat flux to grinding wheel; \( q_{ch} \) is the heat flux taken by chips; and \( q_f \) is the dissipated heat flux inside the contact zone by the lubri-refrigerating fluid. Setting this ratio as \( R_s \), the heat flux that goes into the workpiece is \( q_w \). \( R_s \), typically, the workpiece partition rate \( R_s \), and it varies in accordance with abrasive type, the type of machined steel, the specific grinding energy, lubri-refrigerating fluid and contact length. The heat flux shared by the workpiece and abrasive grinding wheel \( q_{ws} \) is given by the equation rearrangement (2), that is:

\[
q_{ws} = q_w + q_s = q_t - q_{ch} - q_f
\]

(2)
Correlations for the maximum temperatures in contact zone can be presented in several ways. Segundo Zhu, D. et al. (2012) one of the simplest ways for contacts of abrasive machining is given by Equation (4):

\[
T = C R_w \frac{q_0}{\beta_w \sqrt{v_w}} \frac{1}{l_c}
\]

Wherein: \(\beta_w\) is the relative parameter to the thermal properties of the workpiece, given for Equation (5):

\[
\beta_w = \sqrt{(k/\rho c)_w}
\]

At Equation (4), \(C\) is a temperature factor that takes into account the Peclet number, heat flux distribution and geometry. The heat dissipation to the working fluid will occur if the contact zone temperatures remain below the boiling temperature. Since boiling of the fluid is avoided, the heat dissipation to the working fluid is proportional to surface temperature average, \(T_{av}\) to the contact area, \(b.l\), and convection coefficient, \(h\). In general, according to Marinescu et al. (2004) the average temperature on the contact zone is approximately two thirds of the maximum temperature, in such a way that:

\[
T_{max} = \frac{3}{2} h_f T_{max}
\]

Equation (7), which is the maximum temperature on the contact area, can be used:

\[
T_{max} = \frac{3}{2} \frac{q_w}{h_w} = \frac{3}{2} \frac{q_w - q_f}{R_{ws} + h_f}
\]

Equation (7) can be written under the form of a convection coefficient \(h_w\) because of conduction to workpiece, defined by the Equation 8:

\[
h_w = \frac{\beta_w}{2 C} \sqrt{\frac{v_w}{l_c}}
\]

To estimate the \(h\) of the contact area, which is one of the key issues to estimate surface temperature on contact area, an improvement was proposed by Zhu, D. et al. (2012), based on a cross-matrix of grains, in which the involved hypotheses and definitions are as follows:

- A conical grain model is presented in the work of Lavine et al. (1989), where the cone angle is \(\theta\) and the grains on the abrasive wheel surface are neatly arranged by a cross-matrix.
- A prismatic body located between the workpiece and wheel surfaces in the grinding process would be equivalent to a cylinder with the same height and volume, being the diameter defined as the equivalent average diameter of the grain.

Thus, a model for calculating the heat transfer coefficient by convection on the grinding surface was considered by Zhu, D. et al. (2012) and given by Equation (9):

\[
h_f = \frac{N u_f k_f}{L} = \frac{N u_f k_f}{d_g N} = \frac{N u_f k_f}{d_g (l_s/L_g)}
\]

The Nusselt number \(N u_f\) is given by the Equation (10), where: \(k_f\) is the thermal conductivity of the fluid; and \(L\) is the characteristic length. The choice of the characteristic length must be made toward growth direction or based on limit layer thickness. Here, \(L\) is the external diameter of a cylinder in cross flow (perpendicular to cylinder axle) and is equal to the product of the average equivalent diameter of the abrasive \(d_g\) and the number of effective grains \(N\) throughout the direction of the contact length.

\[
N u_f = 0.664 \text{Re}_f^{1/2} \text{Pr}_f^{1/3}
\]

Through modeling considered by Zhu, D. et al. (2012), the calculation of the convective heat transfer coefficient on the workpiece surface can be rewritten through Equation (11), and energy partitioning in the workpiece/wheel.
Analysis of reverse heat transfer for conventional and optimized lubri-cooling methods during tangential surface grinding of ABNT 1020 steel

1.2 The mathematical model: direct and indirect problem

The grinding process can be simulated through the mobile heat-source model by Jaeger (1942), in which the source can be constant, triangular, trapezoidal, or any other form. Considering a half-infinite body moving at speed \( v_w \) in the x direction, and a uniform heat-source, as in Figure 1.

\[
\text{Figure 1} \quad \text{Bi-dimensional thermal problem. Anderson et al. (2008).}
\]

The thermal problem involves a mobile heat-source, as Figure 1 shows, where the direct problem is resolved from the transient bi-dimensional diffusion equation, Equation (13):

\[
k \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] = \rho c \frac{\partial T}{\partial t}
\]

According to Anderson et al. (2008), for calculation convenience and simplification, some hypotheses are used:

a) Grinding process is in steady-state condition.

b) The grinding phenomenon is considered to be a two-dimensional problem.

c) Thermal parameters in workpiece, wheel and chips are constant.

Workpiece temperature depends on the time and heat flow location, which consists of the horizontal and vertical coordinates (x and y). Boundary conditions are shown in the Equations (14) and (15), and the initial condition is given by Equation 16:

\[
q_w(x,t) = -k \frac{\partial T(x,t)}{\partial y} \quad \text{for} \quad -l_c/2 \leq x \leq +l_c/2
\]

\[
-k \frac{\partial T}{\partial y} = hT(x,t) \quad \text{for} \quad y = 0
\]

\[
T(x,y,0) = T_0
\]

Wherein: \( h \) is the transfer coefficient of resultant convective heat of the cutting fluid. Once assumed these considerations, direct problem formulation is enabled. In this paper, the direct problem solution by the numerical method was carried through using the finite volume method for discretization. In accordance with the thermal problem in study, Figure 1, such cells may be subjected to the following bordering conditions:

A. Heat flow prescribed at the border:

\[
T_{\eta} = T_p + \frac{q_{\text{face}} \Delta \beta}{k}
\]
B. Convection heat transfer:

\[
T_\eta = \frac{(2K - h_{faz} \Delta \beta)}{h_{faz} \beta + 2k} T_p + \frac{2 \Delta \beta h_{faz}}{h_{faz} \Delta \beta + 2k} T_{\infty}
\]

(18)

C. Temperature prescribed at the border:

\[
T_\eta = 2T_{faz} - T_p
\]

(19)

Wherein: \(\eta\) represents the border and \(\beta\) direction depending on the adopted axes coordinates.

When applied to thermal problems, inverse techniques consist of determining border and/or initial conditions. This research aimed to attain the heat flow that propagates toward the workpiece using the golden section optimization technique. For inverse problem solution, an algorithm was developed. In the current used technique, inverse problem is reformulated in terms of a minimization problem involving the following functional defined by the squared difference between the experimental temperatures, \(Y\), and temperatures obtained through the numerical thermal model, \(T(q^*)\). Thus, according to Carvalho et al. (2006), the objective function to be minimized can be written as:

\[
F(q^*) = [Y - T(q^*)]^2
\]

(20)

Wherein: \(q^*\) represents the unknown heat flow.

2. Material and methods

The experiments were carried out in a tangential surface grinder, equipped with one 300-mm diameter aluminum oxide grinding wheel of Norton brand. Proof-bodies used in trials consisted of a rectangular workpiece of steel plate ABNT 1020 with dimensions of 100 x 36 x 12.7 mm. Thermal properties of the grinding wheel, workpiece and cutting fluid are presented in Table1. Two-wire K-type thermocouples connected to the data acquisition system were used in the trials as in Figure 2. An acoustic emission sensor of Sensis manufacturer, DM-42 model, was attached to the machine table and coupled to a processing and engine electrical power measurement modules to read the signals and activate the wheel. Regarding temperature, firstly, the thermocouple (that supplies millivolts) was directly connected to the data acquisition plate of National Instruments, USB 6009 model, which is compatible with Lab View software.

| Thermal Properties | \(k\) (W. m\(^{-1}\). K\(^{-1}\)) | \(\rho\) (kg. m\(^{-3}\)) | \(c\) (J. kg\(^{-1}\). K\(^{-1}\)) | \(\beta\) (J. m\(^{-2}\). s\(^{-1/2}\). K\(^{-1}\)) | \(a\) (m\(^2\). s\(^{-1}\)) |
|---------------------|---------|-------------|--------------|----------------|----------------|
| Aluminum oxide grinding wheel | 35 | 3.980 | 765 | 10.323 | 1.15x10\(^{-5}\) |
| Workpiece | 63.9 | 7.832 | 434 | 14.738 | 18.8x10\(^{-6}\) |
| Semi-synthetic soluble oil | 0.14 | 870 | 2.100 | 506 | 7.66x10\(^{-8}\) |

Table 1

Grinding wheel, workpiece and cutting fluid thermal properties.

Thermocouple coupling to the workpiece was another problem to solve. The stronger the connection workpiece-thermocouple is, the faster the response will be (for this purpose, we opted to cut a slit at the thermocouple outlet for better setting on the table). This attachment is very important, since temperature rise occurs in a very short period. For each trial, three proof-bodies were ground. Trials were performed by moving grinding wheel down to a specified cutting thickness (30, 45 and 60 μm), for each wheel passing on the workpiece. These values represent finishing situations, medium and rough grinding, respectively. The total volume of removed material at each trial was 7.62 x 10\(^{-7}\)m\(^3\) that was kept during all operations. Thermocouple \(Y\) position, as all practices, is 1.5 mm below the last wheel pass surface \((Y = 0.03540\) mm), that is, 0.0339 mm from bottom \((0.03540 - 0.0015\) mm). Grinding pass number, \(n\), was calculated in function of the removed volume: 20 for 30 μm; 13 for 45 μm; and 10 for 60 μm cutting depths.
The used cutting fluid in conventional and optimized cooling methods was semi-synthetic soluble oil, used in 1:20 ratio, which equals a 5% concentration fluid in emulsion, applied in an outflow of 4.58 x 10^{-4} m^3 s^{-1} and at a rate of 3 m s^{-1} per application for the conventional method. For the optimized method, we used the same outflow, at a rate of 33 m s^{-1}. The nozzle used in this work was designed in such a way as to cause the least possible turbulence during fluid outlet. Figure 3 illustrates the nozzle positioning during the grinding operation of conventional and optimized methods.

2.1 Results and discussion

2.2 Theoretical conditions and parameters

The common parameters and theoretical conditions of grinding for both optimized and conventional methods of lubri-cooling are wheel diameter \( d_s = 300 \text{mm} \), chip specific energy \( u_{ch} = 6.0 \text{J.mm}^{-3} \), and in terms of \( h \) calculation through the Equation (11) and \( R_{ws} \) by Equation (12):

\[
\mu_f = 1.002 \times 10^{-3} \text{kg.m}^{-1} \text{s}^{-1}, \quad \theta = 106^\circ, \quad g = 100 \text{ and } V_g = 100\%. \text{ Cut and workpiece speeds were adjusted to } 33 \text{ m.s}^{-1} \text{ and } 1.98 \text{ m.min}^{-1}, \text{ respectively.}
\]

2.3 Numerical and experimental results

All practices follow a nomenclature for proper identification; for example, the optimized lubri-cooling at 30 \( \mu \text{m} \) cutting depth of workpiece 3, passing time 19: OTP-30-3-19. By data analysis of the inverse solution results, the maximum temperature on the workpiece surface is quantified during the grinding process. The thermocouple Y position, as in all practices, is 1.5 mm below the last wheel pass surface \( Y = 0.03540 \text{ mm} \); that is, 0.0339 mm from bottom \( (0.03540 - 0.0015 \text{ mm}) \). We used the "Visit 2.6" software to determine the maximum surface temperature during grinding. As examples, the inverse model solution is shown graphically for the CONV-60-1-08 practice. The A curve at Figure 4 indicates temperature variation with heat flow positioning at the 3.0252 s instant from source input, at a distance equivalent to \( Y \) of wheel passing onto this grinded surface; that is, 0.03552 m from the bottom. In addition, the B curve of Figure 4 refers to the temperature variation with heat flow positioning, where the Y distance is equal to the thermocouple location.
It is noticed in Figure 4 that the maximum temperature on the grinding surface is 110.6°C, being a superficial temperature increase of 75.10 °C. The heat flow estimation for the workpiece was 2,164,912 W.m⁻². Maximum increases on temperature at the contact area (three-replication average for each trial) were compared analytically and experimentally. A graphical comparison between the maximum superficial increase of conventional and optimized methods throughout practices and the cutting depths of 30, 45 and 60 μm are illustrated in Figure 5.

### 2.4 Theoretical result analyses

Once the heat flow that propagates over workpiece is known, \( q_s \), as the inverse problem solution (target function), Tables 2 and 3 show calculated results of parameters covered in item 1.1 in accordance with the model proposed by Zhu, D. et al. (2012) for conventional and optimized methods of fluid application.

#### Table 2
Energy partitioning (conventional method).

| \( a \) (μm) | \( q_w \) (W/m²) | \( q_s \) (W/m²) | \( q_{ch} \) (W/m²) | \( q_f \) (W/m²) | \( q_{total} \) (W/m²) | \( R_w \) | \( R_s \) | \( R_{ch} \) | \( R_f \) |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 1,727,903 | 330,423 | 743,400 | 694,393 | 3,496,119 | 0.494 | 0.095 | 0.213 | 0.199 |
| 45 | 1,984,963 | 399,540 | 910,475 | 801,083 | 4,096,061 | 0.485 | 0.098 | 0.222 | 0.196 |
| 60 | 2,164,912 | 445,872 | 1,051,326 | 1,001,457 | 4,673,567 | 0.463 | 0.098 | 0.225 | 0.214 |

#### Table 3
Energy partitioning (optimized method).

| \( a \) (μm) | \( q_w \) (W/m²) | \( q_s \) (W/m²) | \( q_{ch} \) (W/m²) | \( q_f \) (W/m²) | \( q_{total} \) (W/m²) | \( R_w \) | \( R_s \) | \( R_{ch} \) | \( R_f \) |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 276,977 | 52,966 | 743,400 | 111,309 | 1,184,651 | 0.234 | 0.045 | 0.628 | 0.094 |
| 45 | 516,307 | 103,924 | 910,475 | 208,369 | 1,739,075 | 0.297 | 0.060 | 0.524 | 0.120 |
| 60 | 817,649 | 172,175 | 1,051,326 | 378,233 | 2,419,383 | 0.338 | 0.071 | 0.435 | 0.156 |
A graphical comparison of the energy partitioning and heat flow, for both conventional and optimized methods (at 60µm cutting depth) is illustrated in Figure 6:

Based on results shown in Tables. 2 and 3, we can verify that thermal flux, when compared to the conventional technique method of fluid application, was reduced by 84.0% in the practices performed with a cutting depth of 30µm, at 74.0% in practices having a cutting depth of 45µm and 61.2% in the aggressive practices of 60µm. Contact area temperatures were compared experimentally and analytically for both method techniques of fluid application, and there was no significant variation in their reductions, even under the new fluid application technique.

The optimized technique method of fluid application was effective in reducing the surface temperature of the regions outside the cutting zone, which indicated that the up front and back grinding area cooling process had small influence on the maximum temperature increase at the cutting zone, where the cooling effect on the contact area is negligible. The convection coefficient of the fluid was observed at the contact area for three grinding conditions, and it was similar to the approximate value of $h_c=23,000\text{W.m}^{-2}\text{K}$ as mentioned by Jin et al. (2003). The average coefficients of heat transfer by laminar free convection estimated at lateral surfaces were $10\text{W.m}^{-2}\text{K}$. Convective coefficients in the northern surface were of $1,170\text{W.m}^{-2}\text{K}$ for the conventional method, and $3,883\text{W.m}^{-2}\text{K}$ for the optimized one, which were calculated in agreement to correlations proposed by Incropera et al. (2008) for forced convection in plain surfaces.

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3. Conclusion

The optimized lubri-cooling performance was investigated and compared with the conventional one in an “upgrinding” process, in which the conventional aluminum wheel (Al₂O₃) and the workpiece move in opposite directions. For the inverse problem solution, we used temperatures experimentally measured of heat diffusion equation and external conditions to generate the thermal profile and by using the Golden Section technique, the heat flux, was determined. It was observed that the cooling through convection had a great influence on the heat removal outside the contact area, which is necessary to prevent possible thermal damages on the workpiece surface; however, the cutting region did not have significant temperature reductions. This is due to fluid penetration troubles into this region because of its short contact length and, many times because of a hydrodynamics barrier that can be minimized, if the fluid reaches a jet speed outlet similar to cutting wheel speed, to achieve the targeted cutting region. It was verified that temperatures calculated through the model had similar behavior to the experimental ones. There was uncertainty in the experimental measured temperatures due to the action of some factors, such as for example: poor thermocouple attachment onto machined proof-body, thermocouple sensitivity and problems of contact thermal resistance.

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