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

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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 Al_2O_3, 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.

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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. However, in dry grinding, as there is no cutting fluid to transfer the heat from the contact zone, problems frequently occur in terms of thermal damage on the workpiece surface, as well as poor surface integrity compared to conventional technique of method of application fluid. In this work, the complete thermal analysis of surface grinding that has its roots in Marinescu, I.D. *et al.* (2004) is developed, based on an improved grinding temperature model, Zhu, D. *et al.* (2012). The authors considered the grain geometry and distribution.

Based on the complex relationships between the parameters of the grinding process, as well as the great importance of the process in industrial production, modeling and simulation of grinding processes, several studies have been developed. Important existing classical works in literature have solutions of various physical problems related to heat diffusion. Some of the more complex is the important work of Carslaw and Jaeger (1959) in which treated analytical solutions in complex heat diffusion problems were considered, including those involving moving sources occurring in various engineering applications.

In this work the direct problem consists in a formulation that considers the known heat source and attempts to determine the thermal fields from the solution of the heat diffusion equation, by the numerical finite volume method. According to Carvalho, S. R. (2005), for the solution of the inverse problem, the construction of an algorithm that can obtain the identification of the heat flow through an optimization technique is needed, which minimizes the error function defined by the square of the differences between the temperatures measured experimentally and calculated by the thermal model from the direct problem solution.

Thus, it is important to know the amount of energy in the form of heat that is efficiently transferred to the surface of the workpiece, since there is a great possibility of surface thermal damage occurring. One attractive alternative for dry grinding is the optimized method of fluid application. A literature review shows the lack of study on the effects of optimized lubrication in energy partition and increasing temperature during tangential surface grinding. To contribute to help finding the appropriate grinding conditions, the present work has been developed.

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:

$$q_t = \frac{P}{l_c b} = \frac{F_t v_s}{\sqrt{a d_s}\, b} = q_w + q_s + q_{ch} + q_f \qquad (1)$$

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_w the heat flux that goes into the workpiece is q_w= . R_w q_t Typically, the workpiece partition rate R_w, 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:

$$q_{ws} = q_w + q_s = q_t - q_{ch} - q_f \qquad (2)$$

Wherein:

$$R_{ws} = \frac{q_w}{q_w + q_s} \tag{3}$$

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):

$$T = CR_w \frac{q_0}{\beta_w}\sqrt{\frac{l_c}{v_w}} \tag{4}$$

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

$$\beta_w = \sqrt{(k.\rho.c)_w} \tag{5}$$

At Equation (4), C is a temperature factor that takes in 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, $b.l_c$,and convection coefficient, h_f 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:

$$q_f = \frac{2}{3} h_f T_{\max} \tag{6}$$

According to Zhu, D. *et al.* (2012), in case the work fluid did not evaporate, Equation (7), which is the maximum temperature on the contact area, can be used:

$$T_{\max} = \frac{3}{2}\frac{q_w}{h_w} = \frac{3}{2}\frac{q_t - q_{ch}}{h_w/R_{ws} + h_f} \tag{7}$$

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

$$h_w = \frac{3}{2}\frac{\beta}{C}\sqrt{\frac{v_w}{l_c}} \tag{8}$$

To estimate the h_f 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 θ 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):

$$h_f = \frac{Nu_f k_f}{L} = \frac{Nu_f k_f}{d_g N} = \frac{Nu_f k_f}{d_g\left(l_c/L_g\right)} \tag{9}$$

The Nusselt number Nu_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.

$$Nu_f = 0{,}664 \mathrm{Re}_f^{1/2}\, \mathrm{Pr}_f^{1/3} \tag{10}$$

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 interface, R_{ws} in transient operation, is defined by Equation (12):

$$h_f = \frac{0{,}664 v_s^{1/2} L_g^{1/2} k_f}{\nu_f^{1/6} \alpha_f^{1/3} d_g^{1/2} l_c^{1/2}} \tag{11}$$

$$R_{ws} = \left(1 + \frac{0{,}974 k_g}{\beta_w \sqrt{r_0 v_s}} \frac{1}{F} \right)^{-1} \tag{12}$$

Wherein: r_0 represents the effective contact radius of abrasive grains and F a transitory function.

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.

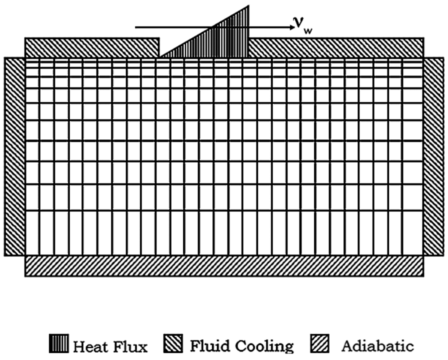

Figure 1
Bi-dimensional thermal problem. Anderson *et al.* (2008).

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):

$$k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] = \rho c \frac{\partial T}{\partial t} \tag{13}$$

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:

$$q_w(x,t) = -k\frac{\partial T(x,t)}{\partial y} \quad \text{for} \quad -l_c/2 \le x \le +l_c/2 \tag{14}$$

$$-k\frac{\partial T}{\partial y} = hT(x,t) \quad \text{for} \quad y = 0 \tag{15}$$

$$T(x,y,0) = T_0 \tag{16}$$

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 discretion. 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:

$$T_\eta = T_P + \frac{q''_{face}\,\Delta\beta}{k} \tag{17}$$

B. Convection heat transfer:

$$T_{\eta} = \left(\frac{2K - h_{face}\,\Delta\beta}{h_{face}\,.\beta + 2k} \right) .T_{P} + \frac{2\Delta\beta h_{face}\,T_{\infty}}{h_{face}\,\Delta\beta + 2k} \tag{18}$$

C. Temperature prescribed at the border:

$$T_{\eta} = 2T_{face} - T_{P} \tag{19}$$

Wherein: η represents the border and β 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:

$$F(q'') = [Y - T(q'')]^{2} \tag{20}$$

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.

Table 1
Grinding wheel, workpiece
and cutting fluid thermal properties.

	Thermal Properties				
	k (W. m$^{-1.}$ K^{-1})	ρ (kg .m^{-3})	c (J. kg$^{-1.}$K^{-1})	β (J. m^{-2}. s$^{-1/2}$ .K^{-1})	α (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}

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.

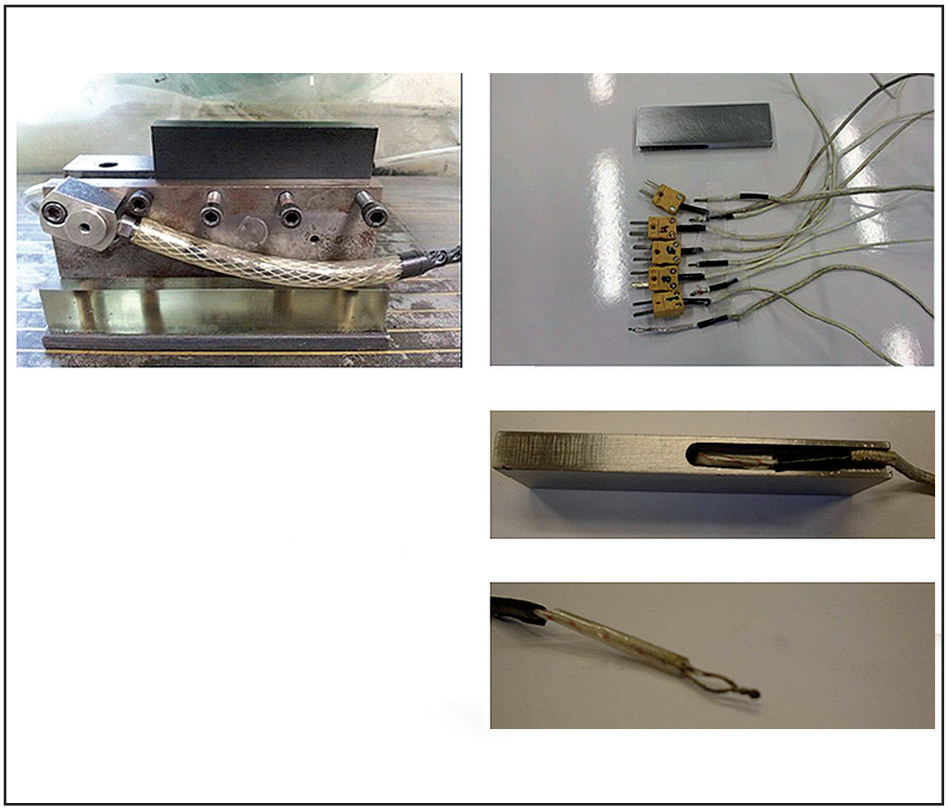

Figure 2
Proof-body attachment
onto grinding table and thermocouples.

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 $4.58 \times 10^{-4} m^3.s^{-1}$ 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.

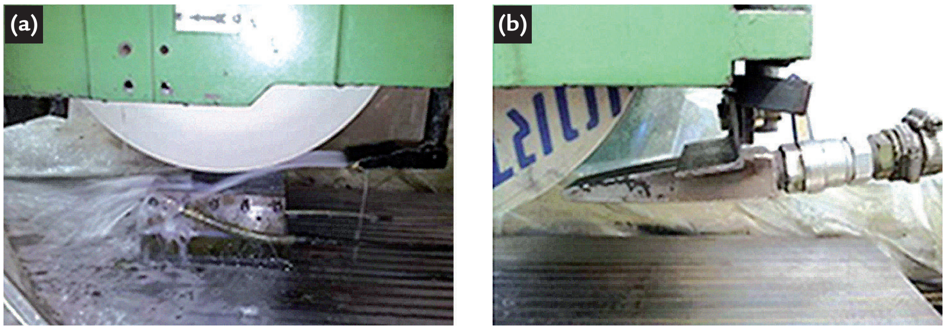

Figure 3
Nozzle positioning:
(a) in conventional method
(b) in optimized method of fluid application.

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 =300mm, chip specific energy u_{ch} = 6.0J.mm^{-3}, and in terms of h_f calculation through the Equation (11) and R_{ws} by Equation (12): μ_f = 1.002x10^{-3}kg.m^{-1}.s^{-1}, θ =106°, g =100 and V_g =100%. Cut and workpiece speeds were adjusted to 33m.s^{-1} and 1.98m.min^{-1}, respectively.

2.3 Numerical and experimental results

All practices follow a nomenclature for proper identification; for example, the optimized lubri-cooling at 30 μm 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 mm); that is, 0.0339 mm from bottom (0.03540 - 0.0015 mm). We used the "Vislt 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.

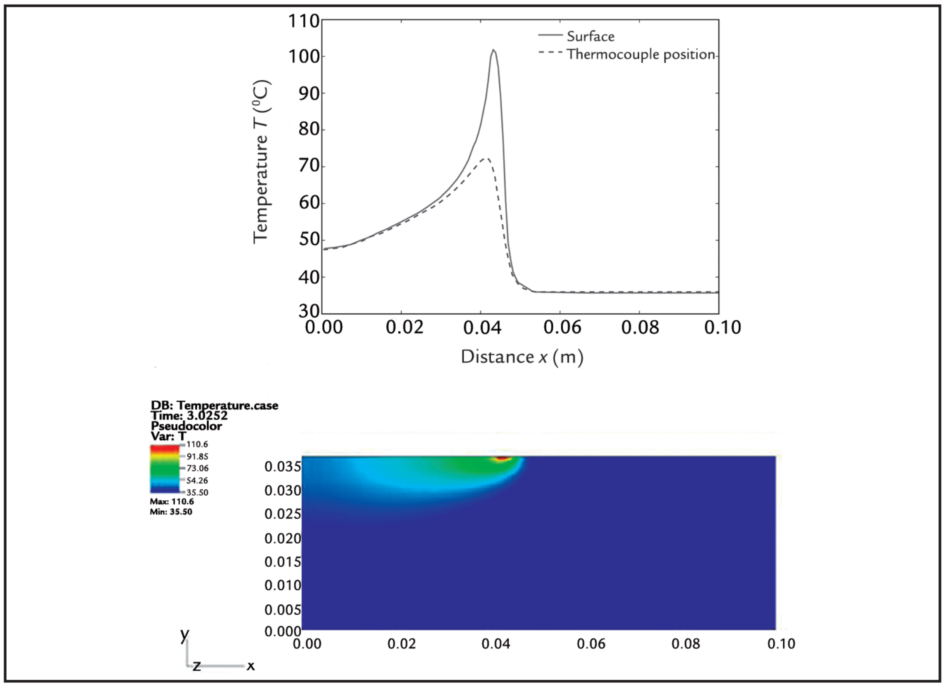

Figure 4
Temperature variation due to heat flow positioning at 3.0252 s instant. CONV-60-1-08 practice.

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.

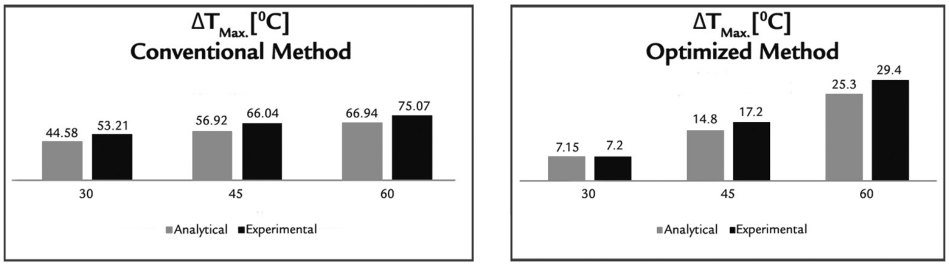

Figure 5
Maximum superficial increase of the optimized method of fluid application. Cutting depths of 30, 45 and 60 μm.

2.4 Theoretical result analyses

Once the heat flow that propagates over workpiece is known, q_w, 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.

		q_w (W/m ²)	q_s (W/m ²)	q_{ch} (W/m ²)	q_f (W/m ²)	q_{total} (W/m ²)	R_w	R_s	R_{ch}	R_f
a (μm)	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 2
Energy partitioning (conventional method).

		q_w (W/m ²)	q_s (W/m ²)	q_{ch} (W/m ²)	q_f (W/m ²)	q_{total} (W/m ²)	R_w	R_s	R_{ch}	R_f
a (μm)	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

Table 3
Energy partitioning (optimized method).

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:

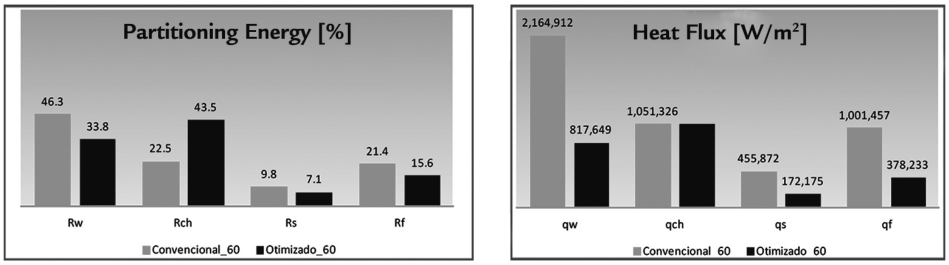

Figure 6
Energy partitioning ratio and heat flows of conventional and optimized methods. 60 μm cutting depth.

Based on results shown in Tables. 2 and 3, we can verified 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 otimized 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_f =23,000W.m^{-2}.K as mentioned by Jin *et al.* (2003). The average coefficients of heat transfer by laminar free convection estimated at lateral surfaces was 10W.m^{-2}.K. Convective coefficients in the northern surface were of 1,170W.m^{-2}.K for the conventional method, and 3,883W.m^{-2}.K for the optimized one, which were calculated in agreement to correlations proposed by Incropera *et al.* (2008) for forced convection in plain surfaces.

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 (Al$_2$O$_3$) 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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