EVALUATION OF TEMPERATURE AND HEAT FLUX DURING HIGH-SPEED TAPPING

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Abstract. *Temperature measurement and heat flux estimation are always a difficult job in machining processes. Several researches have been performed aiming to define the correct percentual of heat flux which is devided to the tool, chip and workpiece. Researches in tapping process are not still very accomplished due to small percentual of its application in machining industries. In this paper the heat flux and temperature into the cutting zone during tapping process are estimated. An analytical methodology based on Inverse Heat Conduction Process was applied to find the heat flux. The temperatures were measured in the workpiece using the embbeded thermocouple technique. The tests were carried out in AISI H13 steel (55 HRC) adopting dry, flooded and MQF conditions. The dry condition is considered as reference in order to compare the heat flux with other machining cooling systems. Solutions based on Jaeger's classical heat source method and mathematical fits were applied and analyzed to find both heat flux in feed direction and temperature into the cutting zone. The results showed that the proposed theoretical model used to estimate the absorbed heat and the convection coefficient for each of the cooling system demonstrated good fitting specially about to the thermocouple T0. Finally the mathematical methods applied to calculate the cutting zone temperature can be also considered as a good initial estimation mostly when working at 2-dimensional domain.*

Keywords: *Tapping Operation, Heat Conduction, Cutting Temperature, Mathematical Models*

1. INTRODUCTION

Since the beginning of the 20th century, when F. W. Taylor used water for the first time to cool cutting operations, a significant increase on tool life was experienced. From this time a large variety of cutting fluids was used for this purpose (Heisel *et al.*, 1998). The use of fluids with lubricating properties, such as oil-based fluids, has also been another very common procedure aiming at longer tool life on selected machining processes. Oil-based fluids can lubricate better than water, which drastically reduces the heat due to friction at contact surfaces and contributes to produce a good surface finishing. Following that, cutting force is also reduced, leading to less power consumption for the whole cutting process. This has also been one of the main reasons to use cutting fluids with lubricating capacity (Belluco and De Chifre, 2001).

Oil-based fluids are commonly emulsified within water (containing 1 to 20% of oil) or used purely without any water addition. Extreme pressure additives can also be applied to reduce the possibilities of adhesion at tool-chip interface (Diniz *et al.*, 2000). Force and power in low speed machining processes, such as drilling, broaching and tapping are strongly influenced by lubricating properties of cutting fluid. In those processes, temperature at the chip formation zone is relatively low and lubricating properties are more significant. Low power consumption corresponds to a good lubrication fluid and it is usually the first choice in industry (Belluco and De Chifre, 2001).

In addition, the current labor and environmental law requirements demand tight control, maintenance, discard and emission of residues into the atmosphere (Aronson, 1995; Klocke 1997; Heisel, 1998). To minimize the use of cutting fluid, two techniques have been intensively tested: dry cutting, also known as ecological machining, and cutting with a minimum quantity of fluid (MQF), where a very low amount of fluid is used (Sales, 2001). The MQF name is given to the process of pulverizing a very small amount of oil (less than 30 ml/h) in a flow of compressed air. Some good results, in terms of tool life, have been obtained with this technique. Recently, Braga *et al.* (2003) used this technique on drilling Aluminum-Silicon alloy (323) with uncoated carbide drills. The authors concluded that MQF could reduce the temperature on the chip formation zone, maintaining it at levels low enough to avoid tool material deterioration.

Nowadays, all machining process employs oil-based fluids with objective of maintain the cutting temperature near the environmental temperature. Tapping is a process that requires the constant use of fluids to cool and minimize the friction during the operation. Tapping is one the most difficult operation in metalworking industry, since it is often performed at final stages and a broken tap often causes a high cost. Cutting fluids are often used in tapping process and are believed to be beneficial to the reduction of tapping forces, temperature and improve thread quality. The friction coefficient for dry sliding between tool-workpiece materials is about 4 times as great as with lubrication fluid. There are only slight differences between the friction coefficients measured with different cutting fluids. Therefore, the use of oil-based cutting fluids reduces tapping force significantly and the application system may also affect the temperature at the cutting zone (Cao and Sutherland, 2002).

Tapping process is widely used for the production of internal threads on a large scale. (Zhang *et al*., 2003). Taps and tapping machines for internal threads are amongst the most complexes and least understood cutting tools and cutting process (Armarego and Chen, 2002). Tapping is a complex cutting process due to the multi-flute/multi-land engagement between the tap cutter and the workpiece hole (Dogra *et al*., 2002). There are few works in the literature investigating heat flux during drilling processes or yet in processes which uses rotative tools (Battaglia and Kusiak, 2005).

According to Ming *et al*., (2003) the temperature distribution on the tool-workpiece interface may be determined with the known heat flux conducting into the tool and the workpiece. Many researchers have developed analytical models to study the thermal aspects of cutting process like the study of Bono and Ni (2002) which estimated the heat flux in drilling process using the Loewen and Shaw's classical model for the heat partition, but it's somewhat overly simplified. This model, for example, was based on the assumption that the temperature induced in the workpiece on the shear plane is analogous to the temperature beneath a frictional slider that dissipates uniform heat flux as it moves with constant speed over the surface of a semi infinite body.

According to Richardson et al. (2006) the heat flux and the thermal partition ratio are unknown quantities in milling and are dependent on the cutting process. Increases in cutting speeds or feed rates will reduce the amount of heat conducted into the workpiece. Increasing cutting speed by a factor of 10 from 300 to 3000 m/min reduces the proportion of energy heating the workpiece by a factor 6. Increasing the feed per tooth by a factor of 3 from 0.1 to 0.3 mm per tooth at a cutting speed of 3000 m/min reduces the proportion of heat conducted by 64% from a partition ratio of 3.6% to 1.3%. Yvonnet *et al.* (2006) used an innovative approach based on the integration of experimental tests, numerical simulations and inverse procedures which was called portioning concept. This methodology permitted to calculate effectively the heat flux distribution flowing into the tool.

Hou and Komanduri (2000) had considered solutions for stationary and moving heat sources using the Jaeger's classical heat source method (Carslaw and Jaeger, 1957). According to author, the usage in general solutions for the temperature rise at any point due to various heat sources provides relevant data in order to determine the flash temperatures. The flash duration plays an important role for optimization of various advanced manufacturing technologies aiming to improve the quality, productivity and costs. For moving heat sources, the location of the point of maximum temperature rise is shown to be different for different Peclet number and heat intensity distributions. Thus, the results obtained show the temperature gradient is steep initially followed by a gradual change with increasing depth.

The experiments carried out at the present work intended to assess the workpiece temperature close to the machined surface on tapping operation using two different fluid application systems. An analytical model was used to define the heat flux in direction of tool moving and a mathematical fit was employed to estimate the temperature in cutting zone. The results were compared to the same operation at dry condition considered as a reference. A theoretical heat conduction model was used to evaluate the heat flux during the tests and the convection coefficient for dry, near dry machining and coolant systems.

2. EXPERIMENTAL WORK

The machining trials involved tapping on AISI H13 steel (14 x 40 x 100 mm) with 50-52 HRC hardness and average chemical composition 0.40% C, 0.95% Si, 0.31% Mn, 0.011% P, 0.006% S, 5% Cr, 0.12% Ni, 1.25% Mo and 0.13% Cu. Taps were single coated (TiAlN - TINAL FUTURA™) M10 x 1.5, straight flute, 100 mm overall length and 24 mm thread length with reinforced shank length according to DIN 371. A milling machining center ROMI model Discovery 560 with 7,500 rpm and 7.5 kW of spindle power was used. The cutting parameters, chosen according to recommendation of tool manufacturer, are shown in Tab. 1.

Table 1. Experimental conditions chosen for the tapping experiments.

Tool manufacturer code	Hole diameter [mm]	Speed [m.min^{-1}]	rpm	Feed rate [mm.min^{-1}]
B1278 TCN-M10	8.6	3.0	95	143

Figure 1 shows a scheme of thermocouples embedded with 0.1 mm distance from external thread diameter, designated as measurement at Dist_0.1. The same configuration was used for distances 2.5 and 5.0 mm, designated as Dist_2.5 and Dist_5.0, respectively. The assembly with the Dist_0.1, Dist_2.5 and Dist_5.0 aimed to determine the average temperature in three different points for each plan of thermocouples axial assembly. Along the tapping distance thermocouples were positioned at depths of 3.0, 7.0 and 11.0 mm from the tap entrance, designated as T0, T1 and T2, respectively.

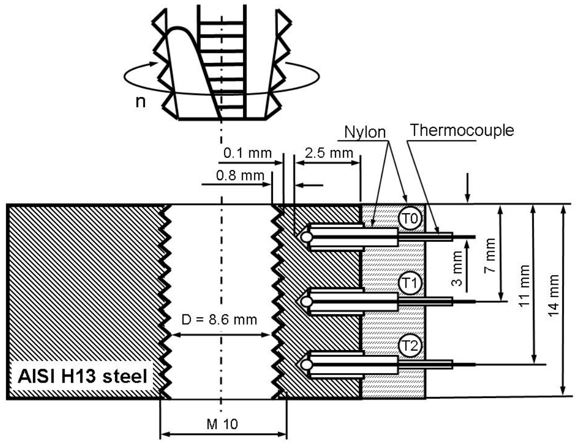


Figure 1. Lay-out of the embedded thermocouples (Example using Dist_0.1 positioned at 0.1 mm from the outer diameter)

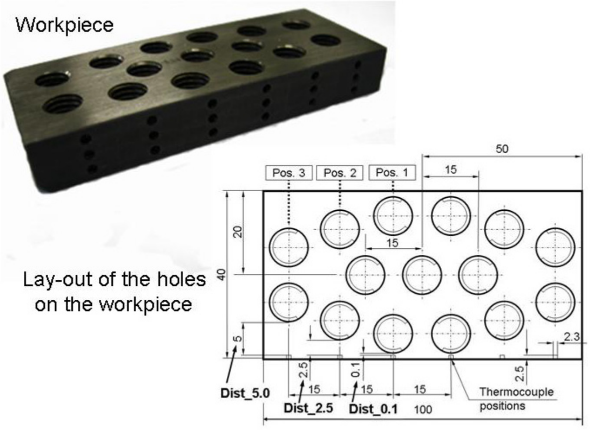


Figure 2. General configuration of holes on the workpiece

Thermocouples type "T" of Copper-Constatan with gauge AWG 30 (0.051 mm^2) and temperature range between -18 to 205 ºC were applied as sensors. A thermostatic bath with ethileno-glicol was used to calibrate them within the range of 10 to 90 ºC. Figure 2 shows the general configuration of holes on the workpiece planned to minimize material usage.

The thermocouples were inserted in holes with 2.3 mm diameter. Tests were replicated twice for each condition. The thermocouples were short and connected to a signal conditioner and card board model PCI - MI0 - 16E - 4 from National Instruments. The acquisition rate for the temperature was configured in 10 Hz. Cutting fluid applied on both systems was BioG 850, a mineral-based oil produced by Microquímica™ with 18 cSt viscosity at 40 ºC.

The system Accu-Lube Precision Applicator model 02A0-STD was employed for MQL condition. The input pressure recommended by supplier should lie between 550 and 1050 kPa being regulated in tests with 590 kPa. The system was set for 20 ml.h-1, with integral mineral oil. Dry tests used the same machining conditions.

Figure 3 shows the set up used for the experiments and Fig. 4 illustrates a scheme of the MQL system. In Figure 4 the word "A" into the circle represent the line that came from the oil tank machine and the word "B" represent the air compressed line that came from the accumulator locate in the laboratory. The holes were initially drilled with single coated TiNAl tools model A3269TFL-8.6 and their diameter was kept within 8.6 $^{\pm 0.02}$ mm. Drilling conditions were 25 m.min^{-1} cutting speed and 0.03 mm.rev^{-1} feed rate.

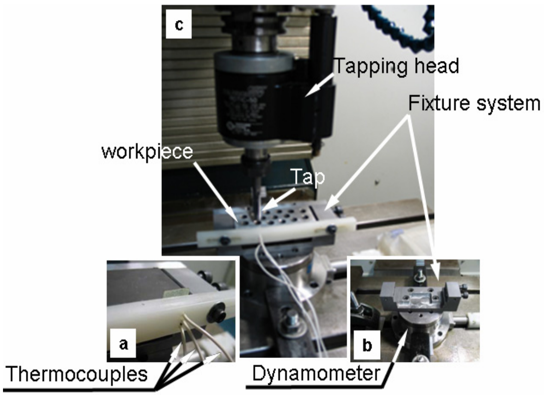


Figure 3. Lay-out of the experiments

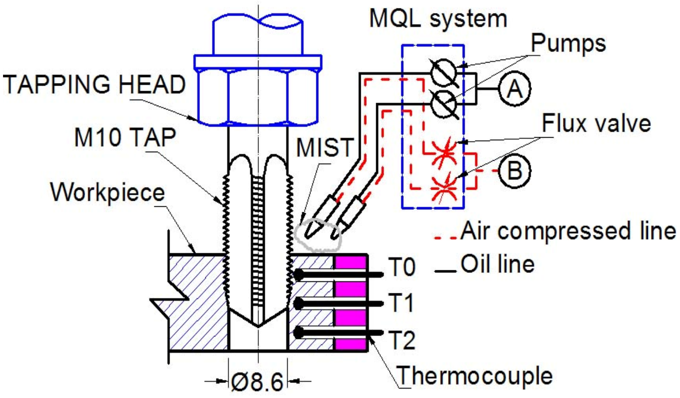


Figure 4. Scheme of the MQL system

2.1. Theoretical heat flux evaluation

To evaluate the temperature analytically the one-dimensional moving heat source theory was adopted. The heat source will move inside a tube whose internal diameter is the hole and the outside diameter the thread outer one. Taking a small part of imaginary tube, as illustrated in Fig. 5, the following energy balance can be written according to Eq. (1):

$$q_x + q_{x+dx} - q_{conv} = \Delta U \tag{1}$$

where $\boldsymbol{q_x}$ = input heat energy due to conduction [W], $\boldsymbol{q_{conv}}$. = output energy due to convection [W], $\boldsymbol{\Delta U}$ = internal energy [W]. The input and output heat fluxes in Eq. [1] have been considerate into the time. The heat source is the result of chip formation plus friction and convection effect is the action of cooling system acting inside the hole. There is a heat flux in the radial direction, but because of the high speed tapping on the axial direction, the flux takes longer to spread and it will not be considered.

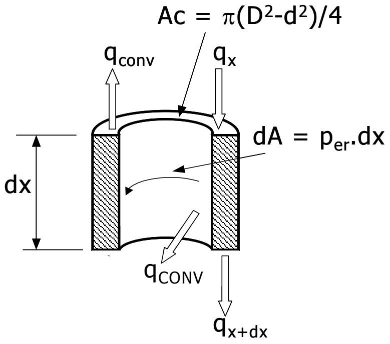


Figure 5. Scheme of energy balance in infinitesimal workpiece

The energy parcels can be written as:

$$q_x - \left(q_x + \frac{\partial q}{\partial x} dx \right) - q_{conv.} = \rho . cp . \frac{\partial T}{\partial t} \tag{2}$$

where d_m = small amount of mass [kg] and c_p = specific heat of the material [J.kg^{-1}.°C^{-1}]. Using Fourier's and Newton's laws for cooling and assuming that heat conductivity k [W.m^{-1}.°C-1] and cross-section area of tube A_c [m^2] are constant in x-axis, it can formulate the Eq. (3) given below. This expression considers the heat source moves at speed v [m.s^{-1}] and other variables are convection coefficient h [W.m^{-2}.°C^{-1}], diffusivity α [m^2.s^{-1}], density ρ [kg.m^{-3}] and time t [s].

$$\boldsymbol{\theta} = \frac{\boldsymbol{q}}{\boldsymbol{2.A_C.\rho.c_p.(\pi.\alpha.t)^{\frac{1}{2}}}} \boldsymbol{exp}^{-v.t-\frac{(x-v.t)^2}{4.\alpha.t}} \tag{3}$$

Equation (3) gives the temperature at a certain point $\boldsymbol{x}$ as a function of time, due to a moving heat source along $\boldsymbol{x}$-axis. This expression allows fitting a curve in experimental data of temperature-time for the best values of $\boldsymbol{q}$ and $\boldsymbol{v}$, which provide the amount of heat absorbed by workpiece as well as convection coefficient. Such coefficient can be associated with the efficiency of the cooling system to remove heat from the workpiece. To fit Eq. (3) into the experimental points the following squared error function was proposed for minimization:

$$\varepsilon = \sum_{i=1}^{N} \left(\theta_i - \hat{\theta}_i \right)^2 \tag{4}$$

where θ_i = theoretical temperature at time i, $\hat{\theta}_i$ = experimental temperature at time i, N = number of measured temperature points. The minimization procedure used a MatLAB™ program applied to temperature curves at positions T0, T1 and T2 separately. Each of these curves was obtained as an average curve using data obtained at Dist_0.1, Dist_2.5 and Dist_5.0 as well as each of their replications. Such procedure led to a unique curve for each depth of tapping. Every curve fitting resulted in a pair of values, q and h, which represents the energy absorbed and the convection coefficient, respectively. The Levenberg-Marquardt technique was used with error fit of 1e^{-10} and iterations number of 10,000. This technique consists in taking the minor data errors that result a difference between experimental and mathematical fit methodology and thus define the correct value for heat flux and convection coefficient.

3. RESULTS AND DISCUSSION

3.1. Temperature measurements

Figures 6, 7 and 8 show typical graphs of temperature at different positions along tapping depth.

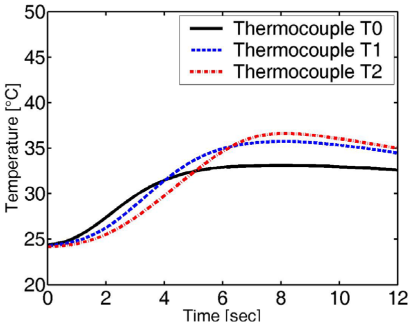


Figure 6. Temperature measured with flooded system

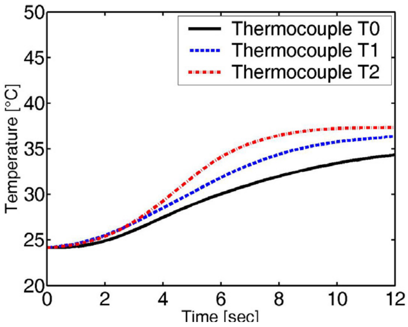


Figure 7. Temperature measured with MQL system

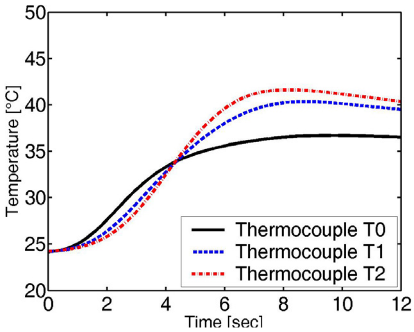


Figure 8. Temperature measured with dry condition

The pattern of the temperature remained approximately the same for all cooling systems tested, and only the peak values varied. The tapping operation lasted about 12 seconds from entrance to return. The lowest peak of temperature always occurred at position T0, at 3.0 mm from the entrance. As the tap goes deeper, more heat is produced and accumulated due to chip formation, followed by the friction between newly formed thread and the tap edges after the chamfered part. The thermocouples positioned ahead of the tool receive and registered the heat wave, since feed rate is relatively low. As the chamfered front passes through the thermocouple position, the temperature tends to fall due to heat conduction, because heat is lost through the workpiece and threaded surfaces. After some time all the workpiece tends to the same temperature as before.

3.2. Fitting heat flux in axial direction

Figures 9, 10 and 11 show examples of curve fitting for different depths of treading using the flooded system as example. It can be observed in Fig. 9 that fits of the experimental and theoretical temperatures for the first thermocouple were almost perfect. Figure 10 however shows that the fitting for the thermocouple at 7.0 mm depth was still acceptable. For the thermocouple at 11.0 mm depth the fitting was still acceptable, but worst of all. Experimental data show a tendency to fall after the peak. The theoretical curve can also reproduce that fall, although slower than the experimental data, mainly for the last thermocouples. It indicates heat is lost faster at the bottom of the workpiece than the theoretical equation is capable of modelling. It could be some inaccuracy on the value of α, which was supposed to be $8.06e^{-6}$ in the present work. This was observed as a general pattern for all cooling systems.

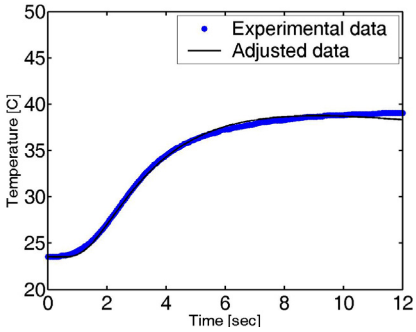


Figure 9. Curve fitting for thermocouple at T0 depth and flooded system.

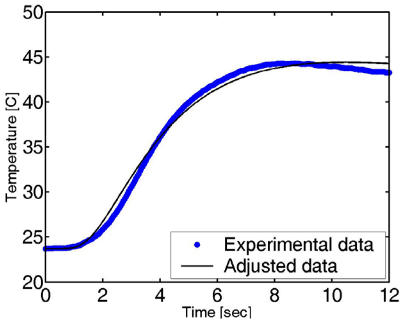


Figure 10. Curve fitting for thermocouple T1 and flooded system.

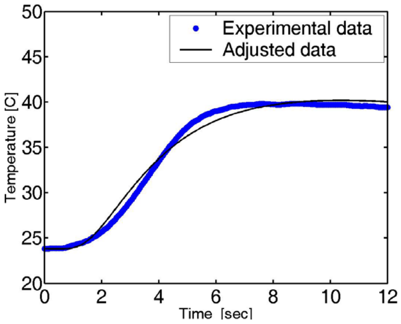


Figure 11. Curve fitting for thermocouple T2 and flooded system.

Estimated values for energy and convection coefficient are shown in Tab. 2. When comparing flooded and dry cutting it noticed that there is a general tendency of increasing the heat absorption and the convection coefficient. As the heat source goes deep the temperature increases and the heat wave goes inside workpiece faster than the tool, reaching the thermocouple ahead. This thermal behaviour creates a higher temperature gradient which makes the convection coefficient increase as well. Comparing the average ***h*** value, no significant difference was found between both systems. That could be expected because the heat lost by convection inside the hole and workpiece faces is very poor, since the area and gradient are small as well as time is short. Therefore, the curve fitting can give an indication of what magnitude of convection coefficient can be expected in tapping. When analysing the data from MQL cooling system in Tab. 2, it is seen a very distinct pattern. The compressed air flow decreased the temperature gradient between room air and the hole wall. It may also have created an air flow underneath the plate. On average, the heat absorption was lower than the flooded system, but the heat removal capacity, expressed by convection coefficient, was the smallest, since the gradient was strongly reduced by the compressed air flow.

Table 2. Values of heat flux and convection coefficient for all tests

Thermocouple	**Flooded**		**MQL**		**Dry**	
	Q [W]	**h [W.m^{-2}.C^{-1}]**	**Q [W]**	**h [W.m^{-2}.C^{-1}]**	**Q [W]**	**h [W.m^{-2}.C^{-1}]**
T0	48.3	40.0	73.4	59.0	72.8	43.0
T1	67.3	45.0	86.0	6.0	102.1	47.0
T2	77.4	50.0	9.4	5.0	112.1	50.0
Average value	64.3	45.0	56.3	23.0	95.7	47.0

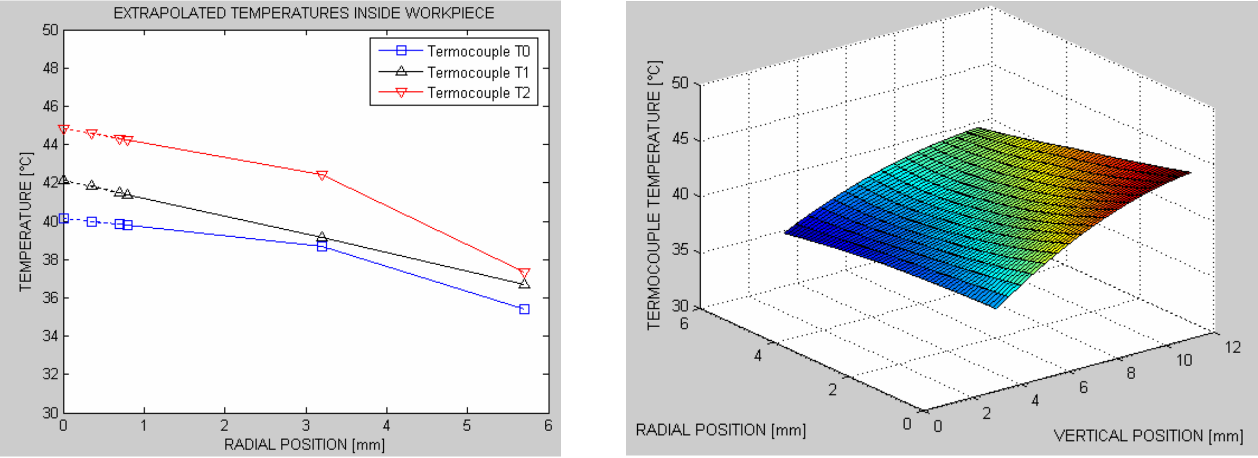
3.3. Temperature estimation in cutting zone

Two methodologies were used to define the temperature into the cutting zone. According Trent (1996), three distinct regions are available into the cutting zone: primary region where the chip is sheared and great heat is generated, secondary region which is the interface chip-tool rake face and finally the tertiary region, formed by interface workpiece-tool clearance face. The temperature percentage for each region is complex and difficult of defining, but some authors considering 90% to the first, 10% to the second and 10% to the third (Shaw, 1988; Trent, 2000, Hou and Komanduri, 2000).

The strategy to estimate the temperature into the cutting zone based on analytical methodology that used the MatLAB program. This analytical methodology was applied by two different ways. The first used an extrapolation method in order to calculate the temperature considering the axial and radial thermocouple positioning. Thus, the function of two variables z=f(x,y) or T=f(radial position, axial position) was interpolated on domain [x,y]. Analyzing the physical problem, the domain was [0.1,5.0], but when solving the mathematical problem, the domain needed to be moved to [0,5.7] aiming to consider the thread. Therefore, despite the extrapolation interval is small [0,0.8], it was considered in calculation. After extrapolating, whole bi-dimensional domain was interpolated and the heat distribution theory was applied in order to define the temperature profile.

The second methodology used a logarithmic curve to fit the experimental temperature points. The logarithmic function was employed because it indicates an asymptotic increase when x tends to zero. This case is more appropriate with cutting theory because the temperature into the cutting zone is higher than any other located in a different region of material, such as when using thermocouples embedded to measure temperature.

Figure 12(a) shows the extrapolation for each set of thermocouples positioned axially regarding to hole at 3.0 mm constant level. This figure is similar to the two cooling systems. Fig. 12(b) shows the experimental temperature interpolation on domain [0,5.7] (radial position of thermocouples) and [3,11] (axial position of thermocouples). It can be observed that the temperature increased in direction of the thermocouple embedded nearest the hole and lowest in axial direction.



(a) one-dimensional extrapolation (b) bi-dimensional interpolation

Figure 12. Temperature estimation for dry test by extrapolation and interpolation methods

It is relevant to emphasize that the same behavior of temperature curves when extrapolating one-dimensionally and interpolating bi-dimensionally were observed for both MQL and flooded tests. Applying the classic temperature partition on machining processes, the temperatures estimated into the cutting zone for dry, MQL and flooded systems were 423.8 °C, 439.1 °C and 358.1 °C, respectively. It can be observed that temperature results in MQL test were close to dry condition and it is suggested that MQL did not reach the cutting zone perfectly characterizing the inefficiency of this cooling process.

Figure 13 shows the surface obtained by interpolating experimental temperatures in domain [0,5.7] (radial position of the thermocouples) and [3,11] (axial position of the thermocouples) for dry condition. Once again it is important to mention this bi-dimensional interpolation method provided similar tendencies for both MQL and flooded tests however with a few differences. In dry case it can be observed that the behavior of temperature increased for the embedded thermocouples placed nearest the hole in radial direction and at 11 mm in axial direction. For other cooling conditions, the greater temperature magnitudes took place in radial positions more distant from tapped hole, but they too concentrated at 11 mm i.e. lower axial position. These slight differences in thermocouple radial position were deeply investigated and occurred due to mathematical effects attributed to interpolation constants. It is vital to comment these differences did not interfere on result analysis. The temperature fitting using the second methodology provided the following values: 402.4 °C, 414.1 °C and 120.9 °C for dry, MQL and flooded condition, respectively.

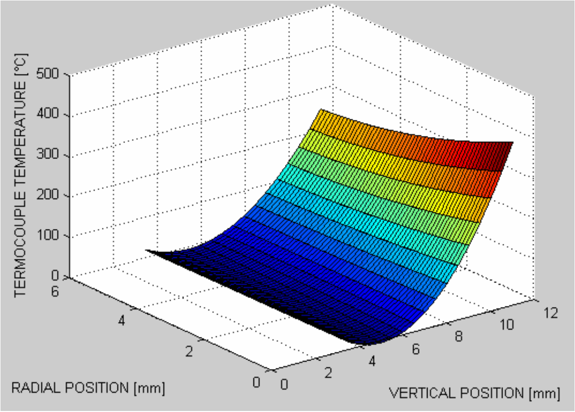


Figure 13. Dry test – Logarithmic fitting with interpolating bi-dimensional

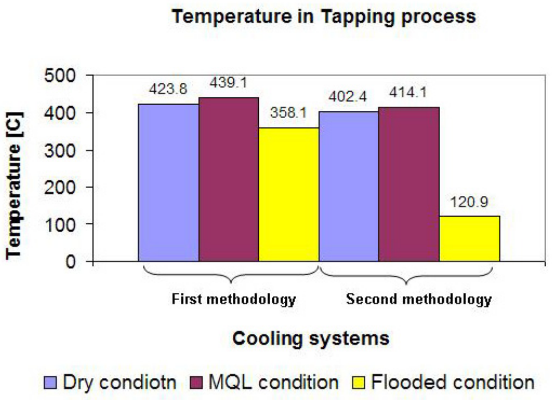


Figure 14. Comparison between fitting methods used in estimation of cutting zone temperature

Figure 14 shows comparative graphic about estimated values of temperature into the cutting zone. It can be observed that the first methodology generated temperature values 5.5% higher than second methodology for the dry and MQL conditions, and 66% for the flooded condition. When verifying each method separately, a tendency pattern can be viewed. The temperature for MQL was 3% higher than dry condition. The use of flooded condition made decrease the temperature about 15% and 70% for the first and second methodology respectively. It is relevant to relate this research work is still in process and requires more investigations about the great difference of temperature estimation between first and second method concerning flooded condition.

4. CONCLUSIONS

The following final conclusions are summarized below:

- When comparing different radial distances (at 0.1, 2.5 and 5.0 mm) curves temperature-time were very similar in shape and presented small variations on the peak values amongst them for each of the cooling systems tested.
- When comparing different depths (axial thermocouple position) temperature peaks increased from the entrance (at 3.0 mm depth) to the exit (at 11.0 mm depth) for each cooling system. The curves were also similar in shape.
- Comparing the cooling systems the temperature peaks were higher when using dry cutting, followed by MQL and flooded system, although the differences have not been significantly high.
- The proposed theoretical model to estimate the absorbed heat and the convection coefficient for each of the cooling system demonstrated to fit the curve at depths of 3.0 from the tap entrance, but differs slightly for 7.0 and 11.0 mm depths.
- The model work better for the flooded and dry cutting conditions, but has a poor fit for the MQL results.
- For the flooded and dry cutting conditions, the model estimates average heat absorption in 74.3 and 95.7 W, respectively. Average values for convection coefficient were 45 and 47 $W.m^{-2}.C^{-1}$ respectively for flooded and dry cutting, which agree with values measured by other authors (Carslaw and Jaeger, 1957).
- Estimated values for MQL system was strongly affected by the compressed air flow introduced into the system. The absorbed heat was smaller than the flooded system, but the convection coefficient resulted in the smallest, due to the reduction in the temperature gradient between surrounding air and hole wall.
- Considering the methodologies employed to define the temperature in cutting zone, the results show good values estimated, except to system with coolant system.
- First methodology supported by extrapolation method and general heat distribution in machining process seems to indicate a good estimation of cutting zone temperature.
- Second methodology based on logarithmic fitting commonly applied in heat conduction of machining process shows certain fitting uncertainties of some temperature points, which caused a difference from first methodology.
- Both methodologies can be considered as a good initial estimation in order to preview the cutting zone temperature mostly when working at 2-dimensional domain, but it is still necessary to approach the heat transfer problem by considering closer thermodynamics properties and restraint conditions.

5. ACKNOWLEDGEMENTS

The authors would like to thank FAPESP for funding and the Production Department of São Carlos Engineering School (EESC-USP) for research development. A special thank to TITEX-PROTOTYP for supplying the tools.

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