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Heat transfer at the grinding interface between glass plate and sintered diamond wheel

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ABSTRACT

Heat transfer analysis is of great importance for temperature prediction during grinding. Indeed the grinding parameters have to be adjusted to accelerate the manufacturing process while minimizing thermal damage to the workpiece. The temperature survey is especially critical for the grinding of glass material because of its low thermal conductivity inducing high temperature rise. In our study, temperatures at different locations in the sintered diamond composites of the grinding wheel are measured using thermocouples and a radio transmission technique. The glass temperature is measured using thermocouple strips on both side of glass plate, the grinding wheel providing the electrical connection between them. Results during grinding with a 6500 rpm rotation velocity shows temperature lower than 80 °C inside the grinding wheel while temperature up to 900 °C is found on glass. An inverse approach is used to compute the wall heat flux and temperature at the wall of the grinding wheel using a 2D axisymmetric heat transfer model. A 1D non linear heat transfer model including conduction and radiation is used to obtain the wall heat flux of the glass material. Knowing temperatures and heat fluxes on both side of the interface, one deduces information on thermal contact resistance, generated heat flux and partition ratio. So, the heat generated by the grinding is estimated between 223 and 399 W depending on the grinding process conditions and is localized on the glass side of the interface. The thermal contact resistance at the glass/sintered diamond composites figures out to be very high with a value greater than 3.8 10^{-3} $m^2K\ W^{-1}$.

1. Introduction

Among the different manufacturing steps of the glass for automotive or building applications, there are a large number of steps which allows reaching the final product. One must distinguish the stages of pre-processing, forming and assembly. The pre-processing includes all manufacturing steps of 2D glass (cutting, grinding, silk screening and pre-cooking). Grinding of the glass plate edges eliminates most of the irregularities after cutting and allows the adjustment of the glass plate to the desired dimensions.

The grinding process requires a large energy input to be consumed in the form of plastic deformation and friction [1]. Indeed, this energy is converted into heat dissipated in the tool, the workpiece, chips and coolant. For glass grinding as this material is of low thermal conductivity, the heat generated may in certain circumstances lead to temperature exceeding the glass transition temperature generating softness and burns. For metal grinding, it may lead to metallurgical changes and a decrease in fatigue resistance [2].

For the analysis of thermal phenomena during the grinding process, most authors use analytical solutions of the heat transfer equation within the workpiece with a surfacic moving source, this resulting from Jaeger's work [3]. In this approach, it is necessary to determine the fraction of the energy supplied as heat to the workpiece in order to estimate its temperature. The generated heat plays a key role in predicting the temperature rise in the workpiece and also in the tool. It often depends on the type of tool shaping, workpiece material and operating conditions. Quantitative values are provided by Malkin [4,5] and Guo [6] who have estimated the energy converted into heat by adjusting calculated temperature of a thermal model in the workpiece with measured temperatures. For shallow grinding with abrasive wheels, this fraction is estimated

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about 60–85% of the supplied mechanical energy, however it decreases to 5% for grinding at low speed and with high cutting depth.

Estimation of the heat flux and heat transfer coefficients to the involved elements of the grinding system is well reported by Rowe [7]. This work deals with the problem of High Efficiency Deep Grinding (HEDG) where high workspeeds and very high removal rates are considered. In this work, the contact between the workpiece and the tool is assumed through a circular surface. It is shown that the temperatures in the contact zone are largely affected by the Peclet number, and the angle between the contacting surfaces. The heat flux dissipated on the workpiece is often assumed to have a uniform or triangular distribution [8,9].

In practice, the knowledge of the generated heat flux and the heat partition ratio between the workpiece and the tool is obtained by using inverse method. Thus, the temperatures are measured by thermocouples located close to the interface [10,11], or by infrared thermography [12]. In these works, the heat transfer equation is solved using a numerical method (finite differences or finite elements). Heat fluxes are then estimated. For deep grinding, the temperature distribution depends on the contribution of the coolant used to remove excess heat in order to prevent the destructive effects of the high temperatures. The corresponding convective heat transfer coefficient is estimated by Jin [13] as function of the grinding zone. All the already mentioned works dedicated to the thermal analysis of grinding are related to metals, the literature does not show heat transfer studies for glass grinding.

In our work, temperature measurements within the grinding wheel are performed during the process of glass grinding. Then, one estimates the temperature and heat flux on the wheel side of the grinding interface using a 2D axisymmetric thermal model and an inverse method. Moreover, knowing the temperature of the glass side interface (measured with thermocouple strips), the wall heat flux is then deduced by a 1D nonlinear thermal model within the glass. The contribution of radiative heat transfer in the glass is taken into account using an effective conductivity and Rosseland's approximation [14]. Finally knowing the heat flow and temperature on both sides of the interface, it is possible to deduce the heat flux generated and its partition ratio between the sintered diamond composites and glass, and finally the possible range of value for the thermal contact resistance.

2. Materials and methods

2.1. Studied grinding process

This work focuses on the processing of float silico-sodo-calcic glass for transport applications. The shaping of flat glass plate is achieved by a grinding wheel of 146.7 mm diameter with a rotation speed of 6500 rpm in an industrial grinding machine (Bystronic). The flat rectangular glass 2.1 mm thick and of dimensions 0.5 × 0.9 m can rotate resulting in an advance speed of the grinding wheel adjustable between 5 and 30 m min^{-1}. The material of the grinding tool is a sintered diamond composite with a 25% volumic amount of diamond particles embedded in a tungsten metallic binder. The thermal property measurement of such composite were performed previously using a technique derived from flash method, weight and volume measurements and also a differential scanning calorimeter [15]. The measured values are 49.2 W m^{-1} K^{-1} for the thermal conductivity, 6620 kg m^{-3} for the density and 462 J kg^{-1} K^{-1} for the heat capacity. The grinding zone is cooled by means of impinging water jets. The grinding process for glass is presented in Fig. 1.

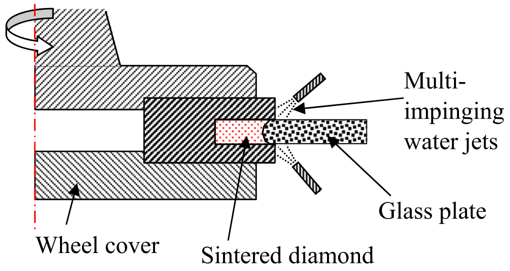

Fig. 1. Grinding process for flat glass plates.

The interaction between the grinding wheel and the glass creates a zone of high temperature which may in certain circumstances exceed the glass transition temperature. Thus, it is important to know the temperature of the glass in the grinding zone and the effect of machining parameters (rotation speed, advance speed, grinding depth and cooling flow rate) on such temperature. Meanwhile, it is important to optimize the cooling device which is composed of multiple water jets impinging the grinding zone. This last step was studied in a previous work [16].

2.2. Interfacial thermal properties

In the grinding process, a movable contact occurs between the workpiece (glass) and the grinding material (sintered diamond). Regarding the heat transfer point of view, this is a thermal problem with an imperfect contact and energy dissipation at the interface. As mentioned by Bardon [17], Laraqi [18] or Bauzin [19], heat transfer at the interface can be described by two equations: one expressing the energy conservation (heat flux equality) and another one describing the temperature drop at the interface. In the first one (Eq. (1)), the generated heat flux φ_g is dissipated on the glass side (φ_1) and on the sintered diamond side $-(-\varphi_2$, with $\varphi_2 < 0)$. In algebraic value, φ_2 is negative due to the propagation of the heat flux toward decreasing x. For the second equation (Eq. (2)) as illustrated in Fig. 2, only the heat flux $\alpha\varphi_g-\varphi_1$ is crossing the interface and is responsible for the temperature drop T_1-T_2 between glass and sintered diamond due to the presence of thermal contact resistance T_{CR}:

$$\varphi_g = \varphi_1 - \varphi_2 \tag{1}$$

$$\alpha\, \varphi_g - \varphi_1 = \frac{T_1 - T_2}{T_{CR}} \tag{2}$$

Therefore, if one is able to measure the wall heat fluxes φ_1 and φ_2 and the wall temperatures T_1 and T_2 on both sides of the interface, one could find information about the generated heat flux φ_g, its partition ratio α and the thermal contact resistance T_{CR}.

In order to perform such analysis, the temperature and heat flux measurement techniques are presented in the following.

2.3. Temperature and heat flux measurement on the grinding wheel

Inside the grinding wheel, stainless steel sheathed type K thermocouples with an overall diameter of 0.5 mm are introduced in different holes performed by electrical discharging through the stainless steel and then in the sintered diamond of the grinded wheel and are accommodated in grooves in the two stainless steel parts holding the grinding material (Fig. 3a). The locations of the thermocouples are presented in Fig. 4. The thermocouples #6, #5 and #4 are respectively 1.35, 2.35 and 5.85 mm far from the grinding interface.

One of the main difficulties for the thermal instrumentation of the wheel is to find a device for temperature measurement and data transmission sufficiently miniature to be installed within the