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Thermal analysis of creep feed grinding

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Abstract

Creep feed grinding is an abrasive finishing process characterized by low feed speeds (0.05-0.5 m/min) and very high depths of cut (0.1-30 mm). Thanks to the extraordinary material removal rate provided together with a high shape accuracy obtained over complex profiles, this process has become the main competitor of milling. However, creep feed grinding has also some limitations that should be overcome. The major limitation is the thermal damage on the machined part and the rapid wheel wear. Since heat distribution depends strongly on the workpiece geometry, a 3D FEM thermal model has been programmed for the generation of a square in order to study the effect of the side wall height on the heat distribution on both, the wall and the ground part. Thermal model has been validated by means of experimental tests being the heat ratio to the workpiece the adjusting parameter. General results show that the higher the side wall, the higher the temperatures. Friction between the wheel and the side wall contributes to higher power consumption.

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Keywords: Creep Feed Grinding; FEM modelling; thermal damage; friction.

1. Introduction

Grinding is a finishing process applied on mechanical components which need tight tolerances and excellent surface quality. Conventional grinding is actually performed with cutting speeds normally between 15 and 60 m/s, maximum depths of 0.1 mm and specific material removal rate from 0.1 to 15 $mm^3/mm \cdot s$. Under these conditions, grinding process has been historically considered as non-economical process due to the extraordinary power

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consumption and low productivity. Nevertheless, the improvement of the mechanical characteristics and dynamics of grinding machines together with a better grinding wheel behavior has marked the evolution of grinding processes.

In the early fifties, however, a new variant of surface grinding known as creep feed grinding appeared. This process aims to reduce process time by minimizing the number of grinding passes. To this end, the depth of cut is increased by several orders of magnitude over conventional grinding (between 0.1 and 10 mm). However, due to the possibility of occurrence of thermal damage on the workpiece, the feed rate is reduced as the depth of cut is increased. Hence, under these conditions specific material removal rates up to 70 $mm^3/mm{\cdot}s$ can be achieved. This process competes with milling in aeronautical applications.

Problems typically associated with conventional grinding as thermal damage of the workpiece could also appear under certain circumstances. There are numerous studies that address the prediction of temperatures during this process [1,2] or estimate heat ratio evacuated through the workpiece [3].

In order to perform creep feed grinding four variants according to the type of wheel and diamond tool used can be found. Thus, Al_2O_3 or CBN grinding wheels can be used and continuous, discontinuous or no sharpening can be applied.

Although the creep feed grinding is successfully used industrially, it is not uncommon to find highly conservative parameters for fear of a heat damaged and of the deformation (due to high normal forces) of high added value parts. Grinding process generates high amount of heat energy, but during creep feed grinding, most of it is dissipated successfully through the chip and cutting fluid, thus minimizing damage to the workpiece. Studies on the heat distribution conclude that the hot spot location on the contact area can be related to the grinding parameters [4]. Thus, it can be stated that when high specific material removal rate together with high depths of cut are achieved (Creep Feed and High Efficiency Deep Grinding conditions), hot spot is located on the material to be removed as chip. In these cases, heat removed by chips is one of the major responsible for the heat dissipation being the second one, the workpiece itself.

The dissipation through the fluid is promoted through low speeds. Although it is believed that the fluid is not directly responsible for the dissipation of temperatures in the contact area, it allows controlling the temperature of the whole piece and a more rapid cooling after the wheel having passed.

Regarding the heat dissipation through the wheel, it depends strongly on the grit material being the CBN the best choice for temperature minimization due to its excellent thermal conductivity.

The study of the heat ratio evacuated through the different elements was carried out by [5-7]. The results indicate that, maintaining all other conditions, grinding with CBN wheels provides better result being R_w as low as 0.2, with respect to the values found by using Al_2O_3 wheels.

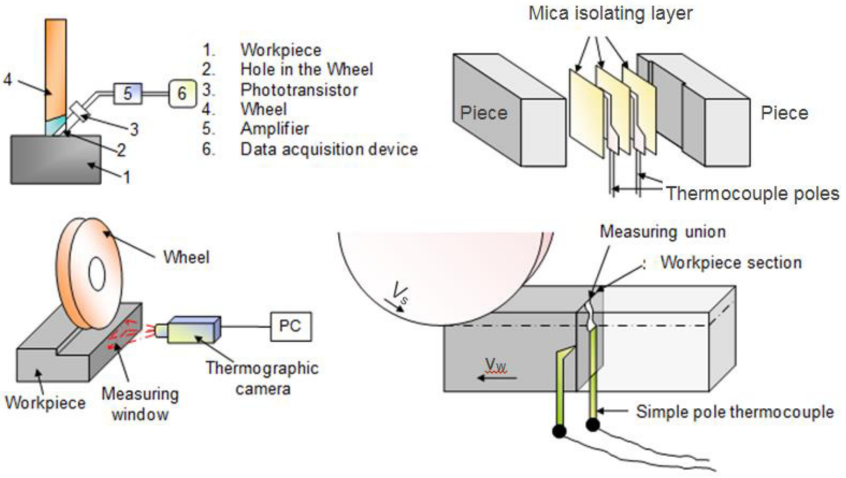

Fig. 1. Different methods for temperature measurement in grinding.

Temperature measurement during grinding is a real challenge since the contact area is not easily accessible/visible and the high gradients higher that 103ºC/s cannot be followed by some sensors. Amongst them, thermography camera is considered as non-contact sensor capable of acquiring temperatures in real time. The disadvantage is that only the temperatures of the visible surfaces can be acquired, therefore no coolant should be used and it is not possible to measure the temperature of the grinding area. In case of inner temperatures were to be acquired, optic fiber together with a pyrometer can be used. Amongst contact methods, thermocouples are the best choice. Thermocouples are robust devices and easy to use but they have some limitations when extremely high gradients appear since they have thermal inertia. This problem can be minimized up to a point through inertia correction. In the case of creep feed grinding gradients can be much lower than in conventional grinding as it will be seen later on from the results of this work. This permits the use of thermocouples without any correction.

Fig. 1 resumes different methodologies for temperature measurement in grinding.

Temperatures in creep feed grinding have been analyzed through both experimental tests and numerical and analytical models [8,9]. However, all studies and models developed until now have considered flat geometries to be ground and, mostly, in 2D. However, industrial practice of this process involves the grinding of complex geometry where the beneficial effect of heat dissipation through chips and coolant are minimized.

This work presents 3D thermal model of creep feed grinding where the thermal effect of the workpiece geometry during grinding a squad is evaluated. The objective is to determine the effect of friction on the sidewall on total consumed power and generated temperatures. Results show that temperatures on the side wall are higher than expected due to the hot spot location.

2. Thermal model description

Thermal modeling of the grinding process is usually based on the consideration of the wheel effect as a heat source moving over the workpiece surface with a velocity of v_w. The value and distribution of the heat source must be correctly defined according to the grinding kinematics and parameters. As stated by Malkin [6], it is assumed that the energy consumed during the grinding process is almost entirely transformed into heat in the contact area between the wheel and workpiece. Its value can be estimated from the following expression:

$$q_t = \frac{F_c \cdot v_c}{b_{seff} \cdot l_c} \tag{1}$$

Where F_c is the tangential force, v_c is the wheel speed, b_{seff} is the wheel width which is actually grinding and l_c is the real contact length.

This heat energy is discharged through the workpiece, the grinding wheel, the chip and the cutting fluid.

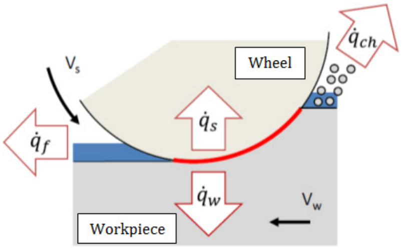

Fig. 2. Heat distribution in grinding.

The heat evacuated into the workpiece can be obtained through the R_w parameter and it is the responsible for the thermal damage of the workpiece.

$$q_t = R_w \cdot q_t + R_s \cdot q_t + R_{ch} \cdot q_t + R_f \cdot q_t \tag{2}$$

$$q_w = R_w \cdot q_t \tag{3}$$

R_w value depends on the workpiece and wheel materials and on the process kinematics, amongst others. Values found in literature for conventional shallow grinding are between 0.45-0.91 [5,9]. However, there is no value nor range encounter for creep feed grinding since in all studies provided values include also the heat evacuated by the chips. In this case, $R_{w,ch,f}$ would represent the heat ratio evacuated by the workpiece itself, the chips and the coolant. This ratio is in the range of 0.1-0.65 depending on whether the application of coolant has been effectively done [5].

Amongst the inputs to the model, there are two whose value is unknown. One is the contact length and the other is the ratio of heat evacuated by the 3 elements represented in the model, this is, by workpiece, chip and cutting fluid.

As it has been mentioned before, creep feed grinding is a deep grinding process where high depths of cut are applied. Under these conditions, the real contact length is, with low error, approximately similar to the geometrical contact length which has been considered for the proposed model in this work:

$$l_c^{\,2} = a_e \cdot d_e \tag{4}$$

Where l_c is the geometrical contact length, a_e is the depth of cut and d_e is the diameter of the wheel.

As the depth of cut is 5 mm, the contact length has been represented as an inclined plane. Ahead of this plane the material is removed in the form of chips. Thank to this configuration the model is able to predict the heat dissipated through the chips as well as through the coolant.

The Fig. 3(a) shows the grinding zone in green, where the most of the heat is generated and transmitted to the workpiece. The Fig. 3(b) shows in red the uncut chip thickness on the left and the simplification of the wheel as a triangular heat source on the right. The heat generation depends on the chip thickness that is the reason why the highest point of the heat source is located ahead the cutting zone, where the chip is thicker. The faces of the workpiece in blue are those where the convection coefficient has been applied.

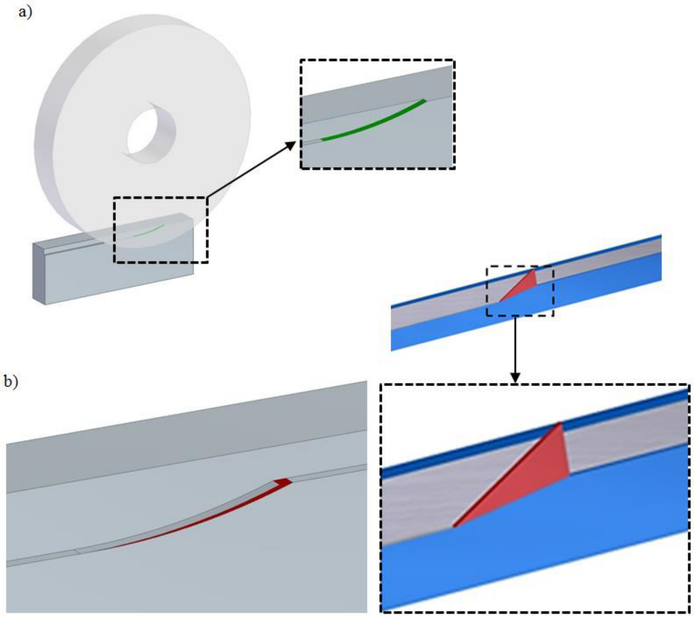

Fig. 3. (a) grinding area. (b) uncut chip thickness and boundary conditions applied to the thermal model.

Model has been programed in ANSYS® software and 8 nodes brick elements have been used. Material properties have been considered as temperature dependent and although the workpiece length used for the experimental validation is about 150 mm, this model just calculates temperatures on the first 50 mm. The reason is that temperatures reach the steady state after the whole wheel has already entered. Time simulation for 50 mm length takes approximately 6 hours (500,000 nodes).

3. Model validation

Model validation has been performed by means of experimental tests. Temperatures have been measured and compared to those predicted by the model. $R_{w,ch,f}$ has been used as adjusting parameter.

3.1 Experimental set up

Model validation needs some data acquisition from the tests, this is, power consumed by the spindle and temperatures measured on the side wall. In order to do that, 3 different tests have been carried out where the side wall height is 0 mm and 10 mm before grinding and with no wall after grinding.

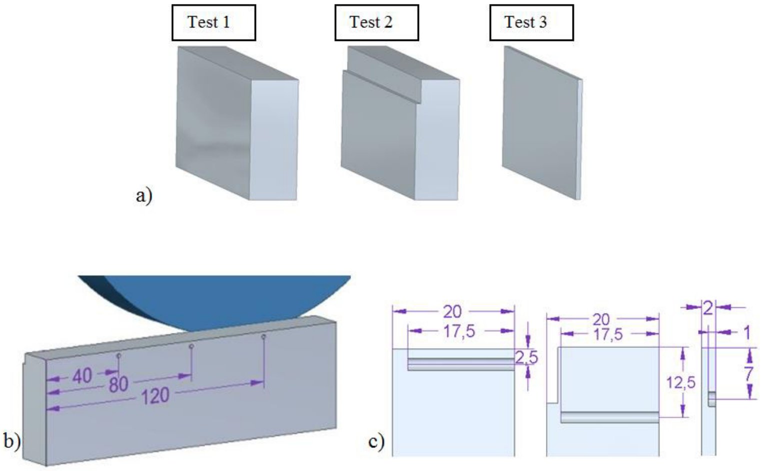

Fig. 4. (a) workpieces geometries before being ground; (b) thermocouples position on the workpiece; (c) depth of the holes for the thermocouples in a ground workpiece

Material of the workpiece is laminated bars of steel AISI 1045. The dimensions are 150 x 60 x 20 mm in the case of the two firsts and 150 x 60 x 2 mm in the case of the third one. The workpieces were sliced by wire EDM, after that, all the surfaces were ground before the tests. The thermocouples are positioned at 40, 80 and 120 mm from the starting grinding surface (Fig. 4(b)) and at 2.5 mm, 12.5 mm and 7 mm respectively from the upper surface, Fig. 4(c).The holes for thermocouple positioning have been machined by sinking EDM, with a theoretical depth of 17.5 mm in the former two cases and 1 mm in the last one, Fig. 4(c). Thus, in case of the thermocouples were welded on the bottom surface of the holes, the temperatures measurements are performed at 0.5 mm from the wall and at three different points along the stroke.

Table 1. Grinding parameters

Grinding parameter	Value
v_s	30 [m/s]
v_w	10 [mm/s]
b_{seff}	2 [mm]
a_e	5 [mm]
q_s	3000
h_{eq}	1,7 [nm]
Q’	50 [mm^3/mm·s]
Coolant: water based emulsion	1 [l/s]

Experimental tests have performed in a BLOHM ORBIT 36 CNC/36 EP grinding machine and 89A46I8AV217 wheel has been used (by Tyrolit). Power acquisition has carried out using UPC-LB by LOAD CONTROLS. Thermocouples are K-type thermocouples and have 0.25 mm in diameter.

Grinding conditions can be observed in Table 1.

3.2 *Thermocouple positioning measurement*

As the value of the measured temperatures depends on the position of the thermocouple, it is necessary to know where exactly they are. In order to do it, workpieces have been cut along the plain containing the axis of each hole by wire EDM process. Exposed thermocouple location can be easily observed by optical microscope and the distance to the ground surface can also be accurately measured.

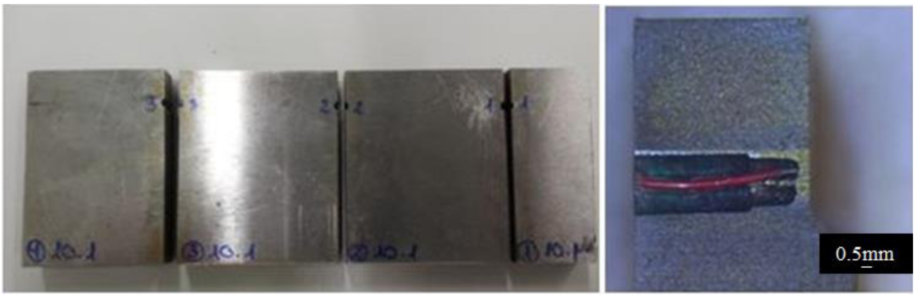

Fig. 5. Workpiece cut by wire EDM and thermocouple location inside the hole.

4. . Results

Validation of the FEM thermal model has performed comparing measured temperatures to the predicted ones. Amongst the thermocouples embedded into the workpiece, next results obtained from the comparison realized to the second one are commented. The reason is that this thermocouple is located in a region where the thermal distribution has already reached steady state regime.

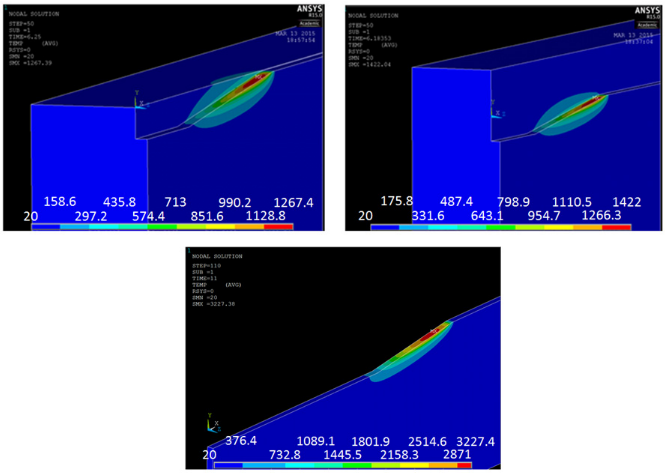

Fig. 6. Temperature distribution for three distinct geometries.

With the aim of having a general picture of the temperatures distribution on the whole workpiece, in Fig. 6 the temperature distribution after grinding three distinct geometries is shown. As expected, temperature values show that the maximum temperature is located in the three cases on the material to be removed as chips founding the maximum temperature in the test 3. In Fig. 7 there are plotted the different values of $R_{w,ch,f}$ that have been tried for each test until they have been absolutely adjusted. The highest value is found in test 3 and it decreases as the height of the wall increases. This means that the heat transmitted to the workpiece, chip and fluid decreases when the contact area between the wheel and workpiece increases and therefore a higher fraction of heat is evacuated by the wheel.

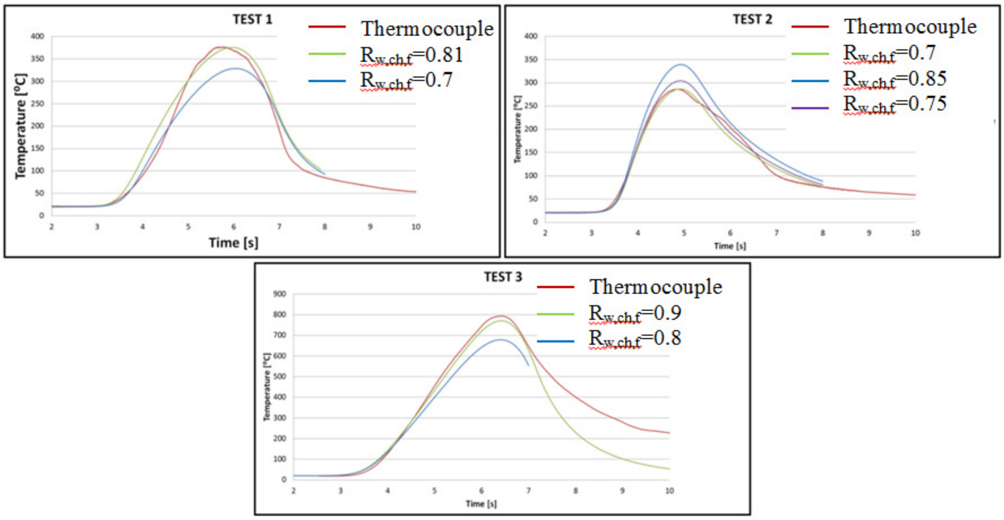

Fig. 7. $R_{w,ch,f}$ values for each test.

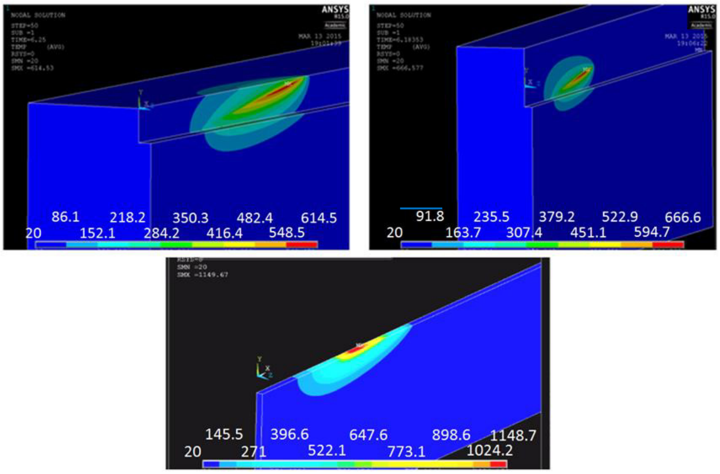

Fig. 8. Temperature distribution on the workpiece surfaces.

However, maximum temperature prediction is not sufficient to know whether thermal damage on the material has been occurred. In order to analyze it, in Fig. 8, the temperature distribution after having removed ground part is shown. As it can be observed in the test 1 and the test 2, there is no thermal damage on the surfaces, being the maximum temperature located on the side wall in both cases. The maximum temperature in the first model is around 614 ºC being around 666 ºC in the second one. Temperatures on the ground surface (bottom surface of the square) are much lower. The reason is that the contact area formed a minimum angle so that the maximum gradients are positioning on the material to be removed. But, this situation could not occur under other grinding conditions and grinding wheel diameter. In fact, although the cutting parameters and the wheel are the same in every test, the maximum temperature reached in the test 3 is 1148.7 ^{O}C causing thermal damage on the workpiece.

5. Conclusions

Creep feed grinding is already an industrial grinding process which competes with milling process in aeronautical sector. However, there are some problems regarding this process that are still far from being solved. In this work, the analysis of the workpiece geometry on the temperature distribution has been study by means of thermal FEM 3D model. To do this, "L" type geometry has proposed and the effect of the height of the side wall evaluated.

Low thermal gradients generated during creep feed grinding permits the use of thermocouples for temperature measurement while using cutting fluid. In measured temperatures, gradients as low as 175ºC/s has been found which implies that measurements have been correctly performed.

General results show that the higher the side wall, the higher is the fraction of heat evacuated by the wheel. The maximum temperatures in test 1 and test 2 are in the same range, but the one of the test 3 is 70% higher, the reason of this raise of the temperature is that this workpiece has less volume of material to dissipate the heat. Friction between the wheel and the side wall neither contributes to higher power consumption nor to a significant increase in the temperature of the workpiece.

During grinding, measured temperatures on the side wall are much higher than those found on the ground surface (bottom surface of the square). The reason is that the hot spot is closer from the side wall than from the bottom surface due to the angle formed by the contact area.

6. Acknowledgements

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