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OPTIMIZATION OF A MULTI-DRILLING SEQUENCE WITH MQL SUPPLY TO MINIMIZE THERMAL DISTORTION OF ALUMINUM PARTS

The drilling process with solid carbide tools with minimum quantity lubrication is under development in the automotive industry due to its high productivity and its environmental benefit. Because of the poor cooling performance when using MQL, a high amount of heat remains in the workpiece, which induces macroscopic thermal distortions and inaccurate parts. This paper presents a methodology to model the thermal distortion of a complex part having a large number of holes. The heat flux entering into the workpiece during each drilling operation is calibrated based on embedded thermocouples and on geometrical observations of the drill surface. Finally, it is shown how the model enables the optimization of a drilling sequence so as to minimize the thermal distortion and the accuracy of the machined part.

1. INTRODUCTION

Nowadays, a large majority of production plants in the automotive industry use the so-called flood cooling lubrication for machining operations such as drilling, tapping, milling, etc. This lubrication has to fulfill the following functions:

1. To reduce friction and cutting tool wear [1];
2. To remove chips from the cutting zone [2];
3. To maintain the machine-tool and the workpiece at the ambient temperature [3];
4. To protect the machine-tool and the workpiece from corrosion.

However, cutting fluids cause serious health troubles (allergies, unhealthy work atmosphere…) as well as huge problems in the field of maintenance [4], which dramatically reduces the efficiency of production plants. A way of improvement is oil mist pulverization also called Minimum Quantity Lubrication (MQL). This lubrication mode is often considered as sustainable [5] since it consumes 106 less cutting fluid than flood cooling (a few milliliters an hour against several hundreds of liters per minute). It has shown its

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efficiency in terms of productivity and cutting tool wear resistance [6],[7],[8]. Unfortunately the thermal regulation (cooling) of workpieces, conventionally obtained by massive watering, is not ensured anymore under MQL. As a consequence, the temperature of the workpiece is modified during the complete machining phase on a machine tool due to the accumulated heat coming from the various cutting operations all around the part, which leads to inhomogeneous temperature fields and as a consequence to a distortion of its geometrical shape. This thermal distortion changes during every cutting operations (several heating phases) and also between two cutting operations (heat transfer in the workpiece and heat exchange with the ambient as well as the clamping system). So, when using the MQL lubrication mode, it is highly necessary to develop a model to predict the instantaneous thermal distortion of components at the macroscopic scale (the whole part) before producing the first real one.

The objective of this paper focuses on modeling the thermal distortion induced by a sequence of drilling operations in an aluminum part under MQL. Indeed, drilling is an embedded operation that concentrates heat in a small volume. It has been highlighted as a critical process regarding thermal distortion [9]. Macroscopic distortion modeling of mechanical parts has been deeply investigated related to high energy processes such as welding [10] or heat treatment [11]. Regarding machining processes, the scientific literature was mainly concerned by the modeling of distortions in thin-walled components due to bulk residual stresses [12], which is a mechanical approach. Macroscopic thermal distortions during machining sequences have only been investigated in turning [13],[14],[15]. To Authors knowledge, macroscopic thermal distortions of complex parts during drilling sequences have not been investigated in the literature. It is only possible to mention some papers concerned by the thermal distortion during a single drilling operation [16],[17]. As a conclusion, a great demand exists to develop a model to predict the macroscopic thermal distortion induced by a sequence of drilling operations.

In order to develop this a thermal distortion model, it is necessary to identify the heat transfer during one drilling operation. Many authors aimed at determining the heat transfer in drilling [9],[16],[17],[18],[19],[20]. These investigations use an inverse heat conduction method. They assume a shape for the heat flux density distribution. Some authors have considered the heat flux as a circle in movement [20], whereas others have modeled a cylinder with an homogeneous heat flux density [17]. Other authors have only considered the effect of cutting edges in front of the tool and not the effect of friction along the margins [16]. On the contrary [9] has pointed out that the backside of a drill (margin + flute) is a key region and that the heat flux density varies from the point of the drill (cutting edges) to the exit of the hole (radiation of chip and friction along margins).

In order to calibrate heat flux models, the most common way consists in embedding several thermocouples in the sample with various distances from the front surface and from the hole's wall [9],[16],[17],[19],[20].

As a summary, the objective of this paper consists in developing a numerical model to predict the 3D macroscopic thermal distortion of an aluminum part induced by a sequence of drilling operations under MQL. The identification of the heat flux density along an elementary hole's wall is made by an inverse heat conduction method considering a moving heat source, combined with several thermocouples embedded in the part.

The principle of this step is presented in Fig. 1. After the calibration step, the model simulates the various moving heat sources in accordance with a drilling sequence of 10 holes on a part (Fig. 2). At the end of the machining phase, and after the cooling phase to the ambient, the accuracy of hole's position is compared with real coordinates obtained by a 3D coordinate measuring machine in order to validate the accuracy of the model. Finally, various strategy of drilling sequence are tested with the model in order to evaluate its capacity to optimize the part's accuracy.

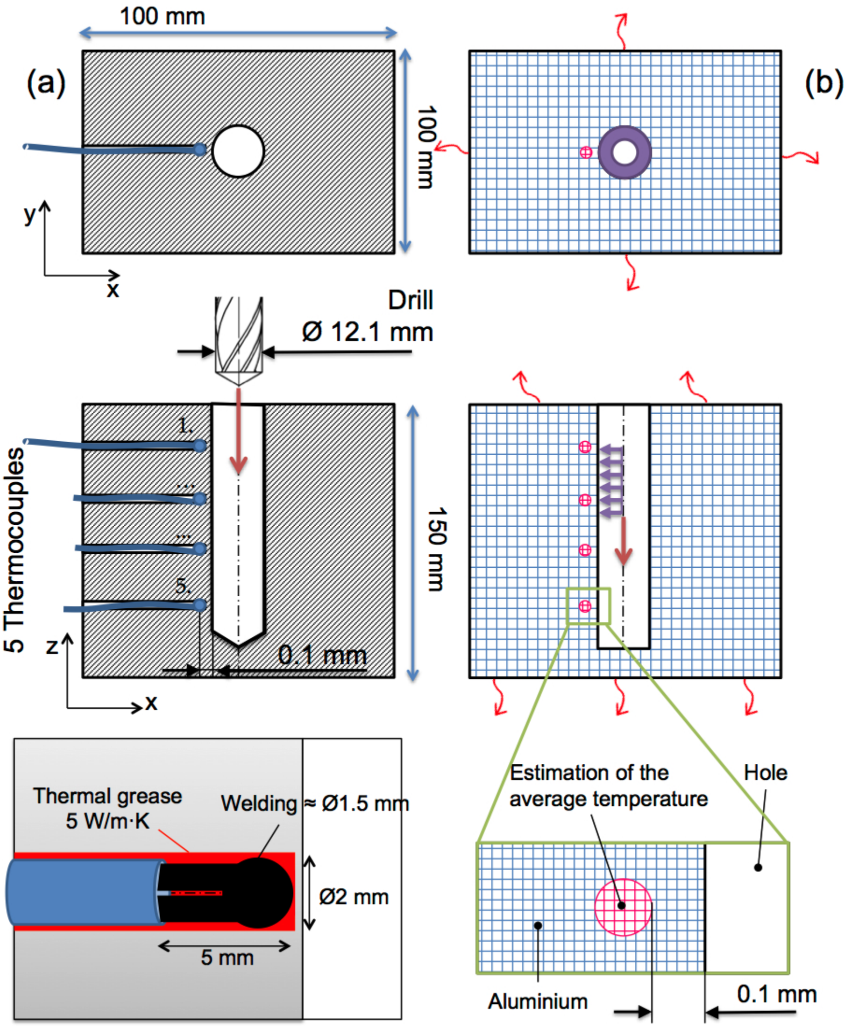

Fig. 1. Principle of the heat flux density identification: (a) Experimental test, (b) Numerical modeling of the test with a moving heat source

2. IDENTIFICATION OF HEAT FLUX DISTRIBUTION IN A SINGLE DRILLING OPERATION

The approach consists in measuring the local temperature close to the machined surface thanks to several thermocouples type K presented in Fig. 1a. In parallel, a numerical model of this experimental protocol is developed (Fig. 1b). A heat flux, with a predetermined shape of density, is applied on the hole's wall. Then, numerical temperatures are extracted in the same region as the one of the real thermocouples and following numerical and experimental values are compared. Finally, the intensity of the heat flux is estimated by iteration until calculated and experimental temperatures become consistent.

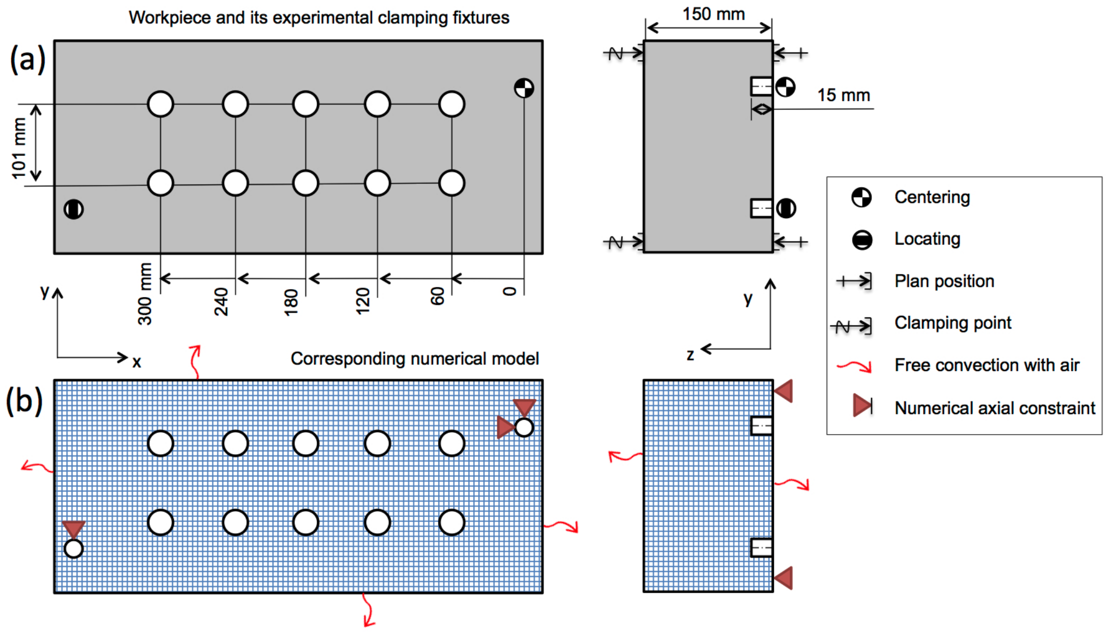

Fig. 2. (a) Workpiece and its clamping system, (b) Modeling of the boundary conditions

2.1. EXPERIMENTAL CONDITIONS

The investigations were carried out on a 4-axis machining-center PCI METEOR GL. Additionally a MQL device with an operating pressure of p = 5.5 bar was supplied trough internal channels of the drill in order to remove chips from the working zone. The flow rate of the straight oil was around 7 ml/h.

The solid carbide drills are uncoated and have a diameter d = 12.1 mm diameter with two helical flutes. The drill has a single margin with a length of l = 170 mm and a double margin close to the point with a length of l = 30 mm. The point angle is 140° angle. The height of the point angle corresponds to 2.2 mm. The cutting conditions have been chosen in accordance with the industrial practice and will be kept constant in this paper: Vc = 190 m/min, f = 0.4 mm/rev. So the axial velocity of the drill is 2 m/min.

2.2. WORKPIECE MATERIAL

The workpiece material is an aluminum alloy with 7% of silicon (AlSi7Mg) typically used in the automotive industry for cylinder head. The samples have been obtained by casting. Its thermally dependent physical properties are listed in Table 1. These properties have been provided by the cylinder head designer Peugeot-Citroen Industry.

The workpiece is clamped on a thermally insulated solid so as to reduce heat dissipation. However the sample can exchange heat with the environment.

Table 1. Aluminum alloy thermally dependent physical properties

Parameter		unit	at 20°C	at 100°C	at 150°C	at 200°C
ρ	Density	kg/m^3	2670	2670	2670	2670
λ	Thermal conductivity	W/(m.K)	125	152	158	163
ε	Expansion coefficient	µm/(m.K)	22.6	22.6	22.6	25.1
C	Specific heat	J/(kg.K)	820	860	900	940

2.3. INSTRUMENTATION

Several thermocouples are embedded in the sample at various depths from the drill entry surface as shown in Fig. 3. The thermocouples are placed x = 0.1 mm away from the drilled hole's wall diameter d = 2 mm holes have been manufactured by EDM (Electrical Discharge Machining) to introduce the thermocouples. The position of the hole's bottom has been controlled by means of a penetration gauge (+/-0.01 mm). Then thermocouples are welded at the hole's bottom with a silver glue having a high thermal conductivity (λ = 5 W/mK). The distance between the welded junction and the sheath has been measured in order to be kept constant around 5 mm. Finally the space between the sheath and the hole is filled with the silver glue so as to minimize the heat transfer disturbances. Some deviations remain in terms of temperature measurement due to the final position of the thermocouple in the hole, as well as some variation due to the silver glue, etc. So each experiment has been replicated 5 times in order to quantify the deviations.

2.4. NUMERICAL MODEL OF THE HEAT MOVING SOURCE

The finite element code Systus® has been employed. The heat moving source technique is used. As presented in Fig. 1, the aluminum samples has been meshed with tetrahedrons having an element size of e = 0.5 mm. The 3D model only considers thermal loads and does not consider the force and the torque of the drill. The calculation step is t = 0.2 second. The calculation duration is around t = 15 min with a workstation having a CPU Pentium 4, 3.6 GHz, 2 GB RAM.

Exchange conditions between the workpiece and its environment are considered in free convection. A λ = 4.2 W/(m^2K) coefficient has been considered for the heat exchange coefficient with the environment [21]. Conduction phenomena with the clamping fixtures are neglected due to the insulated contact material and to the small contact area.

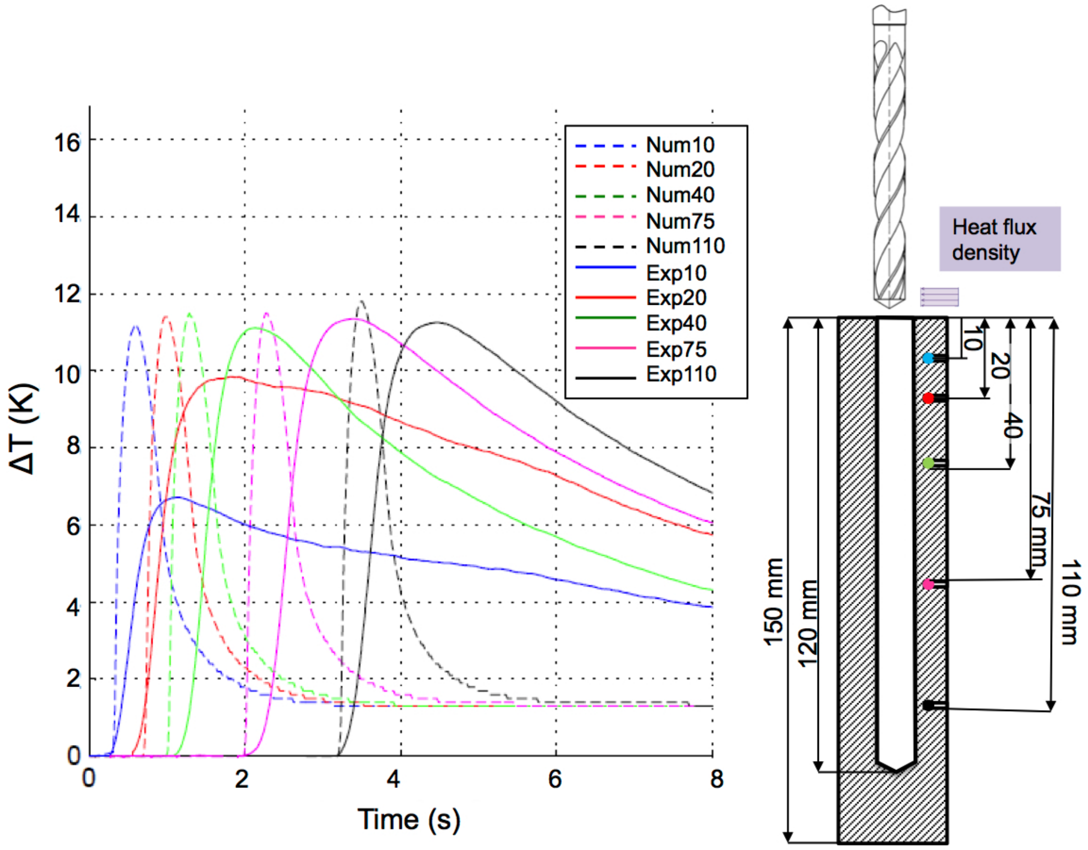

Fig. 3. Evolution of temperatures recorded by thermocouples – comparison of measured and numerically predicted values

2.5. IDENTIFICATION OF A HOMOGENEOUS HEAT FLUX DENSITY

As shown in Fig. 1, the moving heat source is applied onto the finished surface. The velocity of the heat flux corresponds to the feed velocity vf = 2 m/min. The first turn of simulations has assumed a homogeneous heat flux density with a ring shaped all around the hole like [16]. The diameter of the cylinder corresponds to the diameter of the hole and its height corresponds to the height of the drill's point angle (l = 2.2 mm – described in section 2.1). Fig. 3 presents the evolution of the 5 measured temperatures for one drilling test. It is observed that the temperature rises very rapidly when the cutting edges are close to the thermocouple. Then the temperature decreases. In order to fit the heat flux density, its intensity has been adjusted until the numerical maximum temperatures of the thermocouples were in accordance with the experimental values. Of course, due to the deviation in the position of each thermocouple, it is never possible to fit perfectly the 5 maximum temperatures perfectly. So the 4th thermocouple located l = 75 mm from the hole entry surface has been considered with more attention.

It can also be observed (cf. Fig. 3) that the temperature decreases rather slowly in the reality whereas the model predicts a much faster decrease. The same trend has been observed systematically in all experiments.

The areas under the curves provide an estimation of the duration of the heating phase, i.e. of the length of the heat flux density. So it is obvious that this area is much too small in the case of the model, compared to the one of the experimental data. As a consequence, it is clear that the assumed shape of heat flux density is not appropriate for this drilling operation. The shape of the heat flux density should be much larger. The same problem with the homogeneous cylindrical heat flux proposed by [16] has been underlined by [9] in deep hole drilling. This is due to the fact that this model does not consider the friction of the margin on the freshly generated surface, the radiation of the hot chips, the conduction and friction between the chips with the hole and the convection of the oil mist along the flutes [9]. So it has been decided to propose another shape for the heat flux density distribution. Moreover, it is expected that this distribution may be generalized in the future. Thus the parameters describing this distribution have to be related to physical observations on the tool after a drilling operation.

2.6. IDENTIFICATION OF A MORE PHYSICALLY BASED HEAT FLUX DENSITY DISTRIBUTION

Fig. 4 presents four zones with different heat flux density proposed. First it has been assumed that the heat flux density increases linearly in the drill point region. This assumption seems reasonable since the generated heat in the center of the drill has probably few chances to reach the future hole’s surface due to the axial velocity of the drill. On the contrary the heat flux density in the corner may be maximum. Then, the heat generated by friction along the margins has to be considered. The tool used has four margins at the beginning in order to achieve a better guiding of the drill in the hole. Then two margins remains only. It is also known that the solid carbide drill has been ground with a chisel conicity of 0.7% (theoretical value provided by the manufacturer) that limits the friction of the drill, especially for deep holes. So it is for sure that the contact length between the margins and the hole’s wall will be limited. However, it has to be quantified. For this purpose, a drill has been painted with a red ink. During the drilling operation, the ink has been removed from the margins as shown in Fig. 4. In this area, part of the drill has four margins and the rest has only two margins. It is clear that, with four margins, the intensity of the heat generated by friction should be higher. It has been assumed that the heat flux density remains constant and maximum in the ‘four margins’ region. Then, when only two margins are in contact, a linear decrease of the heat density has been assumed until reaching 75% of the maximum value. This proportion has been calibrated within several simulation runs. As a perspective, this value should be more deeply investigated and linked to technical parameters such as margin’s conicity.

Finally, the radiation of the chips and of the oil mist has to be considered all along the two flutes. It is supposed that chips and oil mist are hotter close to the point than close to the outside surface. So a linear decrease of the heat density until zero has been proposed. The length of this zone corresponds to the maximum depth of the hole. This proposed shape is more complex but it has more physical meaning. It remains easy to identify the length of each zone just by observing the drill after one operation.

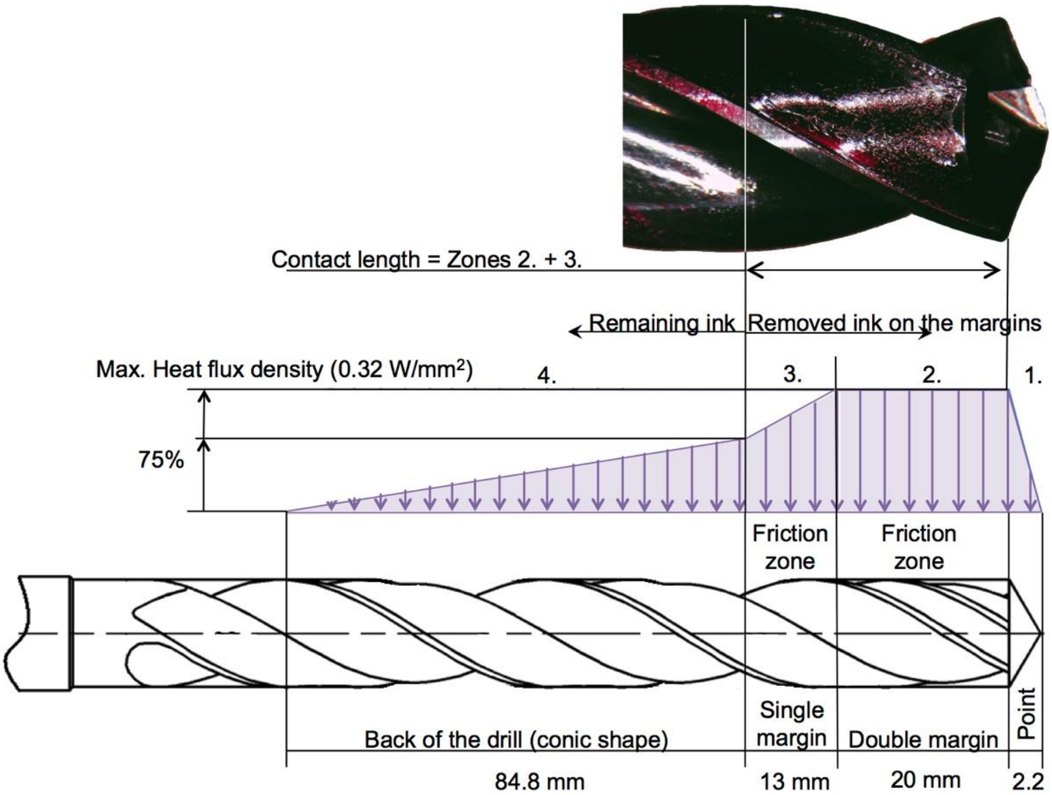

Fig. 4. Heat flux density distribution

This new shape of heat flux density distribution has been used in the numerical model. Its intensity has been calibrated with the peak of temperature obtained on the 4th thermocouple located l = 75 mm from the hole entry surface.

The experimental and numerical temperatures are plotted in Fig. 5a. The peak of temperature of $\Delta T = 11$ K is rapidly reached after less than one second. After 40 seconds, the remaining temperature is only $\Delta T = 1$ K. Experimental and numerical curves correctly fit until their peak value. Then, during the cooling phase, the two curves have a different slope. The model seems to underestimate the temperature during several seconds. Nevertheless, the numerical values do fit with the experimental temperatures after thermal stabilization within t = 35 seconds. After the identification phase, the power transmitted by this drilling operation to the workpiece is around P = 1270 W, which represents 31% of the power consumed by the spindle P = 4100 W (measured by a wattmeter).

It can be considered that the heat flux density distribution can be enhanced even if a very significant improvement has been obtained with this new distribution based on physical observations. The question is now: what is the benefit if more effort is spent to obtain a better fit between experimental and theoretical curves? Indeed, the experimental curves plotted in Figure 5a have been obtained with a new tool. When considering the same drill and the same cutting conditions after 10,000 holes, it can be observed that the power consumption of the spindle increases by 30%. Figure 5b plots the evolution of the temperatures for the five thermocouples and the numerical curves obtained after a third

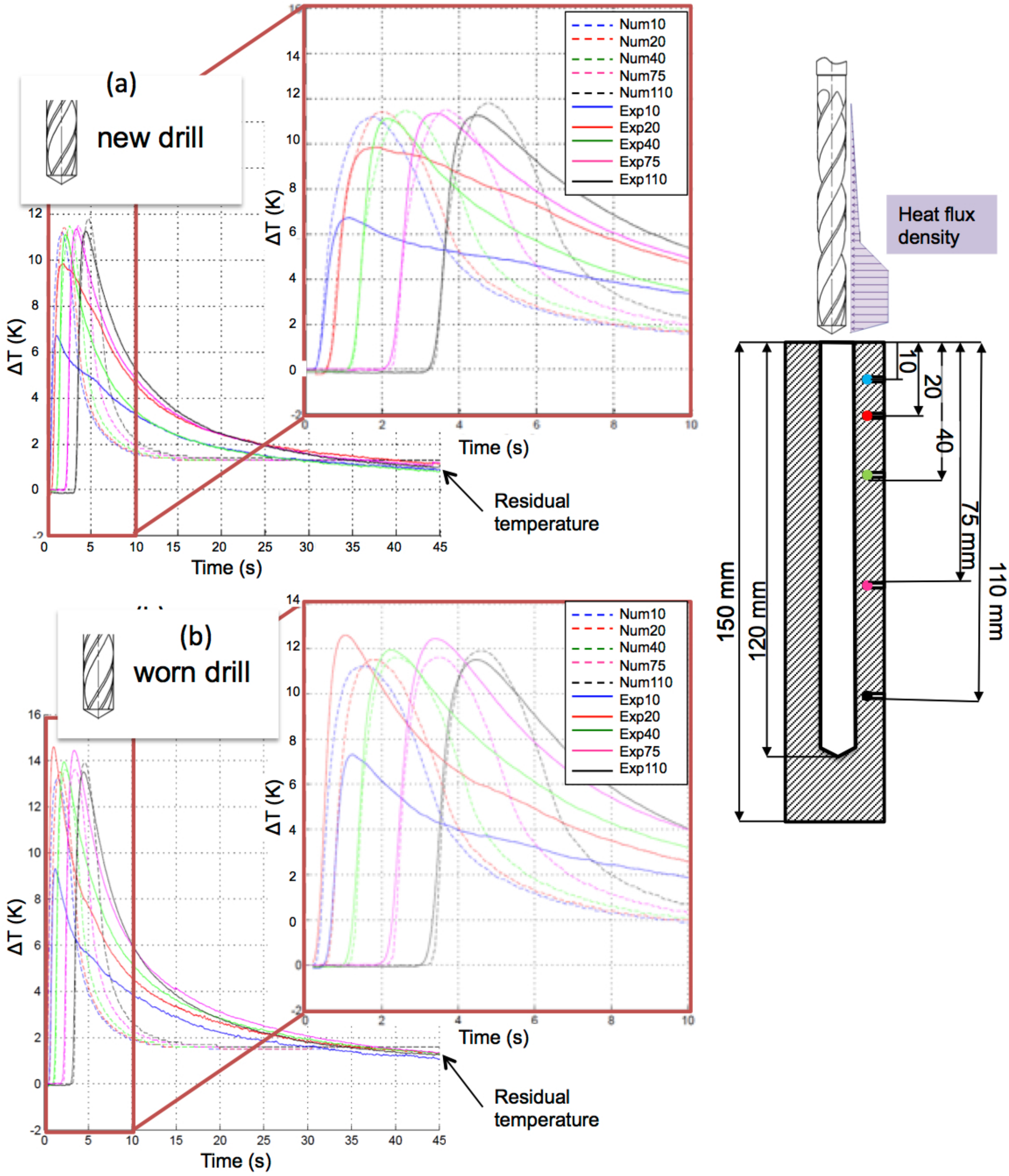

Fig. 5. Evolution of temperatures recorded by thermocouples– comparison of measured and numerically predicted values with: (a) new tool, (b) worn tool

iterative identification. The shape of the curves is similar, but the peaks are now around ΔT =14 K, which is 27% higher than with a new tool. After the stabilization phase, the difference of residual temperature is around 30%. A difference of 30% additional heat in the part will probably lead to a different thermal distortion and to a different geometrical accuracy. However the production plant has to choose a strategy for its drilling sequence irrespective of the tool wear. Probably they should consider an intermediate heat flux density distribution between a new and a worn tool. [17] and [19] have also underlined that the effect of drill's wear is a primary parameter in terms of heat transmitted to the part. As a consequence, it seems questionable to look for a better heat flux density distribution when the objective is to evaluate the thermal distortion at a macroscopic scale. Of course the answer would have been different if the objective would have been to estimate local residual stresses along the hole.

In the next part, heat flux will be applied on the 3D model of a part in which several holes are drilled. The purpose is to determine the deformation of the part induced by a sequence of multiple drilling operations responsible for multiple thermal loads.

3. PREDICTION OF THE MACROSCOPIC THERMAL DISTORTION OF PART WITH 10 HOLES

The objective is to evaluate the thermal distortion of a real part in which 10 holes have to be machined, and to simulate the same drilling sequence within a 3D model. After the cooling phase, the real position of the holes within the workpiece is measured with a coordinate measuring machine, and then compared with the calculated position by the model.

NB: the mechanical behaviour of the workmaterial is considered a elastic in this model.

3.1. EXPERIMENTAL CONDITIONS

Fig. 2 presents the dimensions of the part and the position of the holes. The experimental test has been conducted with new tools only and the same conditions as previously on a machining center at ambient temperature of T = 20°C. This machining operation has been replicated 10 times in order to have an average value of thermal distortion.

We have focused our attention on the position of the holes in the X-Y plan. The distortion in the Z direction has not been investigated. The clamping system was realised in a similar way as in the industrial machining of cylinder heads: two holes have been pre-manufactured. On the top right corner a pin (also called 'centering') is located in the hole which does not enable any movement in X-Y plane. On the bottom left corner, a pin (also called 'locating') enables the displacement in the X-direction but not in the Y direction. Regarding the fixture in the Z direction, the contact surface is limited to some mm^2 in a similar way as in the industrial context, which limits the thermal exchanges. Moreover, a thin disc made of plastic has been introduced at the interface between the fixing elements and the workpiece in order to allow the assumption that no heat exchange between the part and the fixturing system is possible during the experiment.

3.2. 3D NUMERICAL MODEL

A 3D model has been developed using the finite element code Systus®. As previously by a single drilling operation, only the heat transfer has been considered. The part has been modeled with the two holes for the clamping and the 10 holes that should be manufactured. This choice has a consequence on the heat transfer since the missing material areas of the holes are not able to conduct heat. It could have been possible to model the part without holes, but it would have affected also the results since the heat transfer would have been facilitated through holes, which does not represent the reality. The best solution would have been to create holes step by step. Unfortunately, this would have necessitated too complex numerical development, which was not possible in this research program.

The moving heat source previously identified has been applied in each hole with a defined strategy from hole A to hole J by following the alphabetical order. Between two holes, a cooling phase of $t = 0.7$ s has been introduced in order to take into account the movement of the spindle between two holes.

The boundary conditions in terms of displacement are applied in a similar way as on the real part as shown in Figure 2b. Exchange conditions between the workpiece and its environment are considered in free convection. A $\lambda = 4.2$ W/(m²K) coefficient has been considered [21]. Conduction phenomena with the clamping fixtures are neglected due to the insulated contact material and the small contact area. The deformation induced by mechanical forces of the clamping fixture has been preliminary confirmed to be negligible.

The aluminum sample has been meshed with tetrahedrons having an element size of $e = 0.5$ mm. The time discretization used is $t = 0.1$ mm (per simulation step). The minimum displacement quantification is $u = 1$ μm. The calculation time for the sequence with the 10 holes is $t = 11$ h. Results are obtained using low coupling: mechanical iterations are based on thermal maps.

3.3. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

After the cooling phase to the ambient temperature, Fig. 6 shows the displacement of the hole (the position error) compared to its theoretical position without any thermal distortion. Numerical results are plotted in blue color and experimental results green. The bar charts in Fig. 6 plots only the displacement along the X axis since the clamping system allows only the displacement in this direction.

The analysis of Fig. 6 reveals that experimental and numerical results are consistent. Holes, manufactured far from the reference point (for example E and F), exhibit a larger error. So, with this drilling strategy, the error seems to depend directly on the distance between the hole and the reference point. Indeed, after drilling the first hole A, the heat generated leads to an expansion of the part on its left side. As a consequence, the position of the next holes B-C-D-E will be affected. In a similar way, the heat generated by the hole B will affect the next holes on its left side also with a thermal displacement in the same way as the previous one. This leads to a larger displacement for the next holes C-D-E, and so on.

So after each drilling operation, the situation becomes even worse. Of course, between the holes H to J, the error becomes smaller since their distance from the reference point is smaller. Moreover, this zone has more time to exchange heat with the environment.

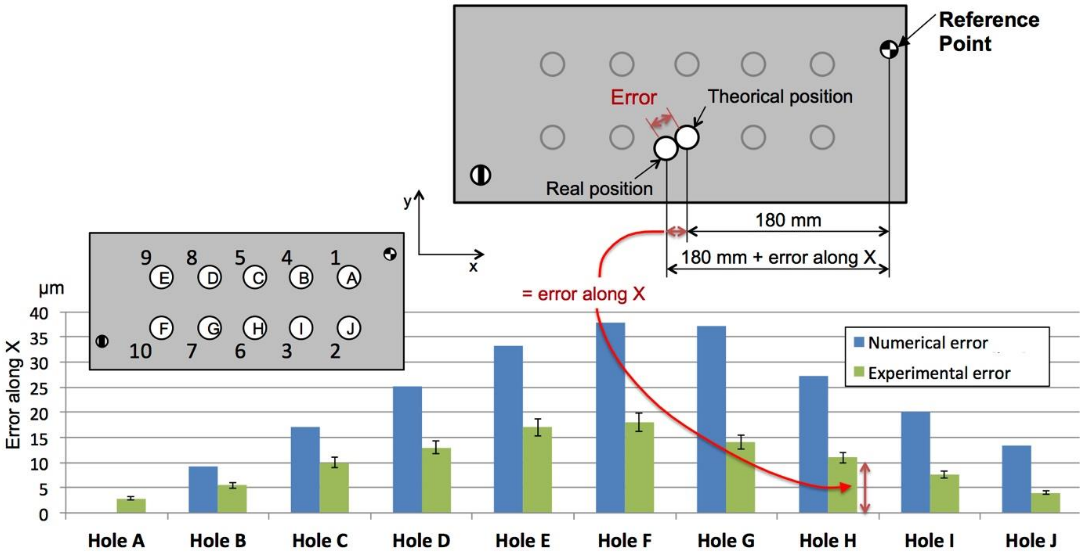

Fig. 6. Experimental vs. numerical position error of the holes in x-direction

Numerical results are consistent with experimental measurements, but the model seems to overestimate the displacement. The difference is assumed to be associated with three aspects:

• Figure 5 has shown that the heat flux density distribution may be improved in order to enhance the fit quality of the identification step (even if the uncertainty due to tool wear has been highlighted);

• The model considers that holes already exist before starting the simulation, which affects the heat transfer. Additionally the moving heat source is applied on the position calculated by the model due to the thermal distortion. In the reality, the position of the drill is controlled by the machine tool, which is not thermally affected. So the position of the moving heat should be improved by considering the real position of the spindle;

• The heat exchange coefficient with the ambient and with the clamping system may be improved by a better calibration;

• The drill used in this experiment is different from the hole used for the identification, but it comes from the batch of the manufacturer. It is well known that some geometrical deviations exist between drills, especially the margin’s conicity that affects the heat generation on the hole’s wall. The effect of this deviation can be a topic for a future improvement of the model.

However, the trend provided by the model is good, but the experimental values are not acceptable for an industrial application since the commonly required accuracy of hole’s position is usually around 0.01 mm. So it is highly necessary to perform an optimization of the drilling sequence so as to minimize this distortion.

3.4. NUMERICAL OPTIMIZATION OF THE DRILLING STRATEGY

Fig. 7 shows the numerical results obtained for four drilling sequence strategies:

• The strategy I has been investigated previously;

• The strategy II aims at distributing the heat in various areas of the machined part in order to reach a more homogeneous workpiece temperature;

• The strategy III aims at producing the holes from the reference point to the extremity;

• The strategy IV aims at producing the holes from the extremity to the reference point.

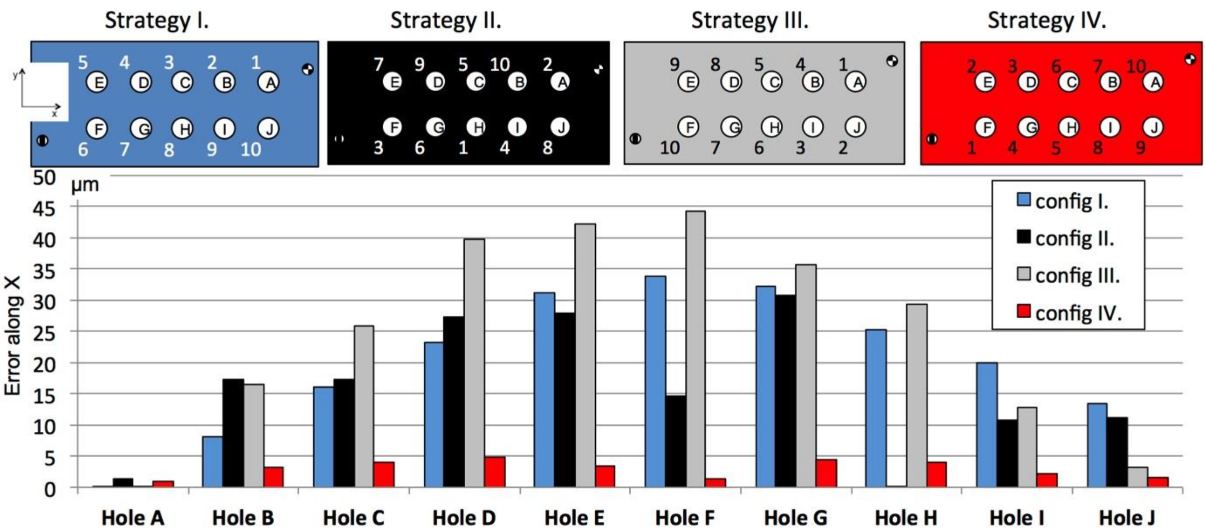

Fig. 7. Position error in x-direction (workpiece length) of holes A to J according to I, II, III, and IV strategies

Fig. 7 reveals that the strategy IV is the best one to minimize the position error. Indeed, by starting with the holes F and E, the heat generated will expand the part on the left, whereas the next holes are machined on the right. So the heat generated by a hole on its right side tends to counterbalance the expansion induced by the previous one on the left side. On the contrary the holes already machined on the right side, move wider from their theoretical position, but this has no influence on the final position after the cooling phase.

Based on this model, it appears clearly that the proposed model enables to validate the best drilling strategy that minimizes the consequences of the thermal distortion on the geometrical accuracy. Moreover, the best strategy achieves to reach an acceptable accuracy of the hole’s position considering the industrial specifications of cylinder heads.

4. CONCLUSION

The aim of the paper was to develop a model to predict the thermal distortion induced by the heat transfer during a drilling sequence of several holes with MQL into an aluminum part. The first aim was to identify the heat density distribution along the drill / hole contact surface. It has been shown that the contact length along the margins and the radiation of chips in the flutes, as well as the tool wear are two key parameters. The second contribution was the development of a 3D numerical model based on the moving heat source methodology. This model enables to displace continuously the heat density distribution along one hole and then along the remaining holes as defined by the drilling sequence. During the simulation, the thermal distortion of the part is considered, which enables the prediction of the geometrical accuracy of the final machined part. The model has shown its capability to estimate the geometrical accuracy with the right trend and an acceptable order of magnitude. Finally, it has been shown that the application of this numerical model for various drilling strategies enables the optimization of the drilling sequence so as to optimize the accuracy of the machined part.

As a perspective, the influence of cutting process parameters (cutting speed, feed) as well as drill parameters (angles, diameter, substrate, etc.) should be investigated in order to link the heat density distribution to these parameters. In a second step, this model should be extended to other cutting processes (milling, tapping, etc.).

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