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# Simulating the Heat Distortiion of a Cast Iron Brake Disc during Dry Machining

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**Abstract:** The application of MQL or dry machining in mass production becomes more and more accepted. Dry (MQL) machining is a very efficient solution to reduce the usage of cutting fluids and represents an effective measure for an environmental friendly production. However, these techniques do not benefit any more from the stabilization in temperature obtained with cutting fluids. More important and more heterogeneous increases of the temperature are observed. This leads to distortions of the work piece during machining which are necessary to be taken into account to maintain the geometrical quality of the manufactured surfaces. In this paper, we present a strategy to handle these thermal induced distortions in an industrial context. This strategy couples finite element thermo-elastic simulations and temperature measurements of the work piece. In a first section, we describe a method to identify machined characteristics sensible to part temperature at loading. This method takes into account standard deviation of the process. A solution to adapt tool trajectories with a temperature measurement is proposed. Second part deals with distortions of the part during manufacturing. A method is proposed to simulate distortions along machining. These FEM simulations allow to identify impact of a machining on next operations. An application of the proposed approach for the machining of a cast iron brake disc is presented. Simulations are compared to measurements made in a dry manufacturing line.

**Keywords**: Machining; Finite Element Method (FEM); Heat transfer.

## 1    Introduction

Manufacturers have to reduce their economical and environment impact in order to satisfy cost and legislative demands. One solution is to reduce use of cutting fluids during machining. Going from wet to dry or MQL machining (Weinert et al., 2004) is a big challenge in automotive industry. This article deals with some temperature issues encountered in a mass production line of cast iron (EN GJL 200) brake disc (Figure 3).

In a first section, a short review of literature is done. This review describes some thermal aspects in machining (heat sources and distribution of heat between tool, work piece, chips and environment). Part 3 presents an industrial case of distortion during machining. In part 4, we describe a method to identify characteristic of parts sensible to workshop temperature variation and a solution to adapt automatically the production to part loading temperature. A Finite Element Method (FEM) to estimate distortions of work piece during manufacturing is presented in last section. This method allows prediction of zones affected by thermal distortions during manufacturing. It can help manufacturers to organize operations in line or to correct tool trajectories with heat input due to machining.

## 2    Thermal aspects in machining

Generally, authors consider that about 90 to 100% of energy associated with chip formation is converted to heat during machining. Figure 1 illustrates the five heat sources that could be observed: plastic strain in primary (T1), secondary (T3) and tertiary (T4) shear zone, friction between tool and chip (T3) and friction between tool and work piece (T5).

**Figure 1**  Heat sources during machining
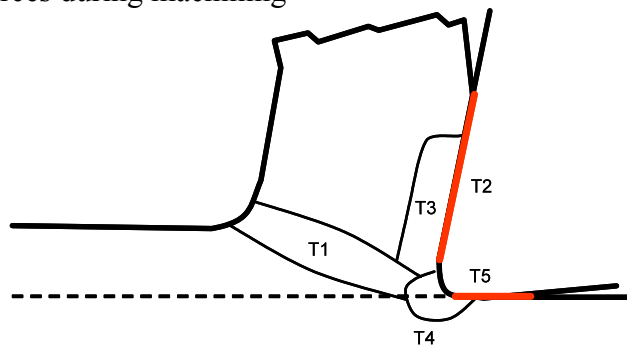


Fleischer et al. (2007) made an extensive literary research to precise repartition of the cutting energy during machining (Table 1). According to the literature, the heat flow into the work piece fluctuates massively. For example, in turning, heat input into work piece is estimated at $1.1 - 20\%$ of the cutting energy.

**Table 1** Distribution of the cutting energy (Fleischer, 2007)

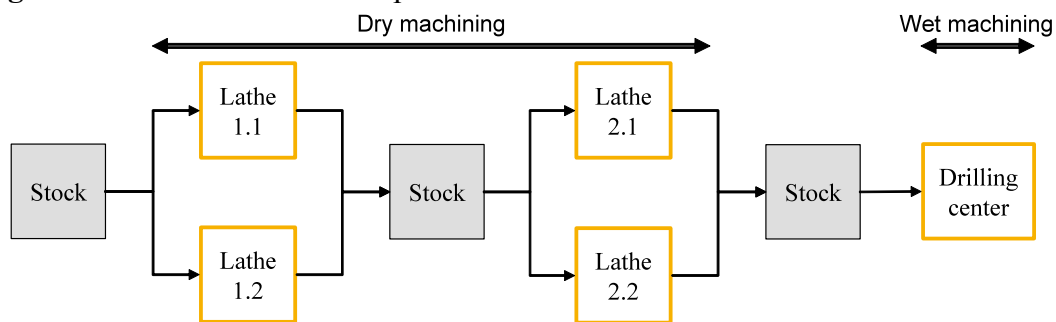|                | Drilling    | **Turning**     | Milling       |
|----------------|-------------|-----------------|---------------|
| Tool           | $5 - 15\%$  | $2.1 - 18\%$    | $5.3 - 10\%$  |
| **Work piece** | $10 - 35\%$ | **$1.1 - 20\%$** | $1,3 - 25\%$ |
| Chip           | $55 - 75\%$ | $1.3 - 25\%$    | $65 - 74,6\%$ |

Many papers deal with tool or chip temperature prediction, there are only a few papers dealing with measurement of heat flow going into part. Authors developed two different approaches. On first hand, authors' aim is to identify partition of cutting power going into part (Komanduri *et al.* 2001, Chou *et al.* 2005). On the other hand, authors directly identify heat input as a function of cutting speeds and tool geometry (Fleischer *et al.* 2007and Pabst *et al.* 2010 for milling operations, Zeilmann *et al.* 2006 and Battaglia *et al.* 2005 for drilling operations).

The literature research shows that the heat input into work piece is dependant of many factors: work piece material machinability, tool geometry and material, cutting conditions, wear, etc.

However precise estimation of the work piece heat input could not be known precisely, orders of magnitude allows to do FEM simulations and to analyse sensibility of parts to machining heat flows.

These temperature variations (due to part loading temperature and temperature rise during machining) affect process robustness, which lead to higher scrape rates. Process has to be watched carefully by operators to adjust machined dimension with parts measurements. These adjustments affect production level.

**Figure 2**  Schematisation of the production line



## 3    Problematic

Brake discs are machined in three steps: two dry turning operations and one wet drilling operation (Figure 2). Parts wait in a stock between each machine tool. For first and second operation, two lathes are disposed in parallel. Parts are machined randomly with one of the two lathes.

**Figure 3**  Studied cast iron brake disc (EN GJL 200)
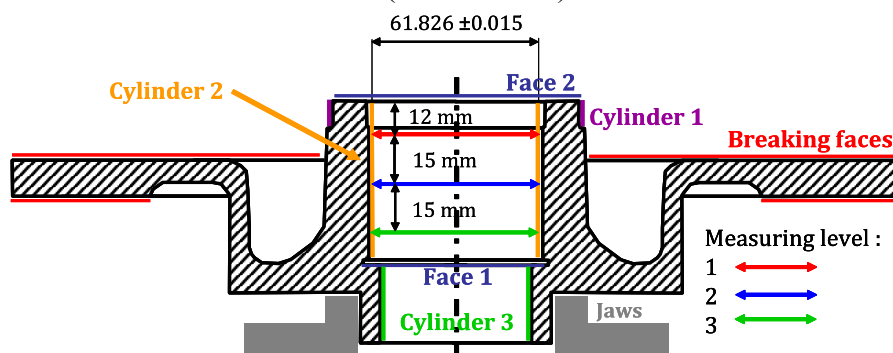
In this paper, a focus is made on cylinder 2 (Figure 3). This cylinder is machined during second dry drilling operation. Two quality issues are encountered for this machining: a variability of mean machined diameter and a form problem (variation of diameter between level 1 and level 3 < 5µm). Cylinder 2 mean diameter has to be machined between 61.811 and 61.841 mm to assure interference of a bearing.

Due to the lack of coolant, work piece temperature varies depending on different reasons: temperature of the workshop, heat flow due to previous machining and waiting time in stock. Figure 4 illustrates evolution of part temperature in the machining line. Temperatures were measured during one week in summer at loading and unloading states. Workshop temperature varies from $T_{min} = 15°C$ to $T_{max} = 34°C$. Temperature rise is from $\Delta T_1 = 8°C$ to $\Delta T_1 = 10°C$ (mean 9°C) for first operation and from $\Delta T_2 = 7°C$ to $\Delta T_2 = 13°C$ (mean 10°C) for second one.

**Figure 4** Brake disc temperature variation along manufacturing line
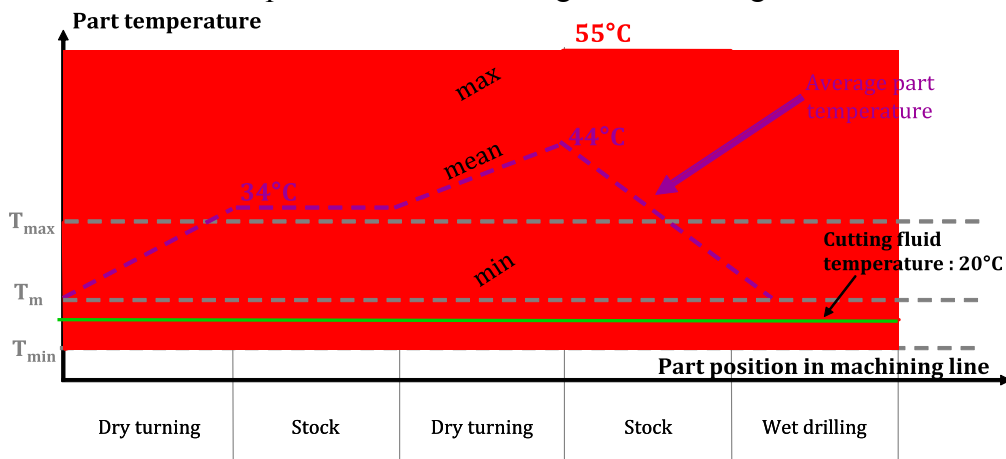


## 4    Method to take into account initial temperature of the part

Machined geometry is linked to part loading temperature. To increase robustness, manufacturers have to stabilize part temperature at loading or to adapt production to initial part temperature.
At loading, temperature of the work piece depends on many factors; prediction of this temperature is not possible easily. If manufacturers know influence of a homogeneous temperature increase on part distortion, they can easily adapt their production to temperature. The following section, present a method to identify on a part which characteristics are sensible to thermal distortions.

### 5.1.   *Identification of characteristics sensible to thermal distortions*

To identify which characteristic of part are sensible to thermal distortion, it is firstly necessary to estimate variability of the process ($\sigma$) without influence of temperature. Figure 5 shows for a one-dimension characteristic, influence of temperature on machined dimension.

To have 99.73% of parts in tolerance we have to be sure that equation:

$$6.\sigma < IT \tag{1}$$

is right (for a centered process).

For a one-dimensional structure of length $l$, thermal distortion introduces a new dispersion $\Delta l$ of process that is independent of previous process dispersion. This new deviation is represented on figure 5 for an intern characteristic and a positive variation of temperature $\Delta T$. Thermal distortion is given by the following equation:

$$\Delta l = \alpha.l.\Delta T \tag{2}$$

with $\Delta l$ distortion for length l, α coefficient of thermal expansion, $\Delta T$ difference between part temperature and reference temperature (generally 20°C).

**Figure 5** Brake Example of result to estimate standard deviation of the process in one dimension
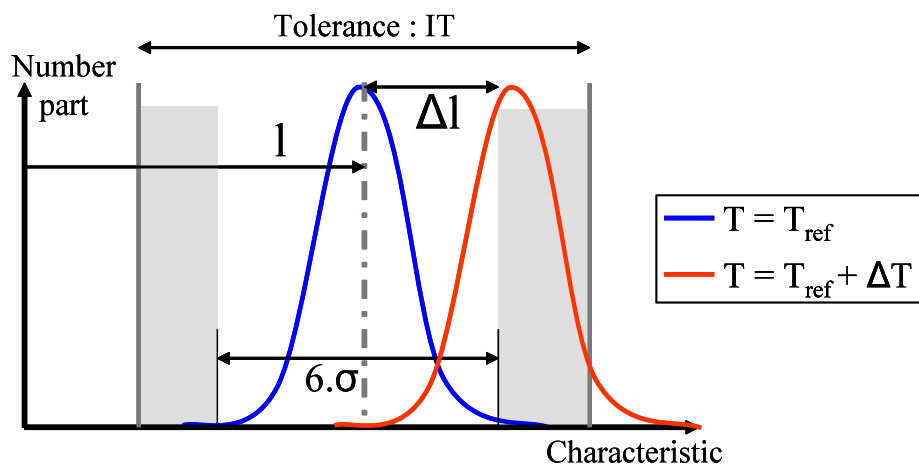


Taking into account thermal deformation, equation (1) become:

$$\left|\Delta l\right| + 6.\sigma < IT \tag{3}$$

Maximum temperature deviation allowed is given by:

$$\Delta T = \frac{IT - 6.\sigma}{\alpha.l.} \tag{4}$$

For instance, the diameter of cylinder 2 (figure 3), finished during second operation, has to be machined between 61.811 mm and 61.841mm. Standard deviation of the process with cooling is σ = 3 µm. Coefficient of thermal expansion is about α = 10.5µm/(m.K) for EN GJL 200 cast iron (Table 2). In order to produce in tolerance, part-loading temperature has not to vary more than 4°C between machine tool adjustment and start of machining for the part.

**Table 2** Parameters for FEM simulations, cast iron EN GJL 200

| Specific Heat | Density | Thermal conductivity | Coefficient of thermal expansion |
|---|---|---|---|
| 550 J / (Kg.K) | 7 200 Kg/m³ | 46 W / (m.K) | 10,5 µm / (m.K) |

Equation (4) could be interpreted in a different way. When manufacturers use cutting fluids, they generally stabilize temperature of the liquid. This criteria illustrate maximum temperature variation allowed for the cutting fluid between two machine tool adjustments.

*5.2. Correction of part loading temperature*

Figure 6 illustrates correction implementation in machining program. Temperature measurement, made at loading is used to compute correctors. Then machining could begin. Some validations are done to avoid machining problems (comparison to last temperature measurement, control of temperature value …).

**Figure 6** Correction implementation in machining program

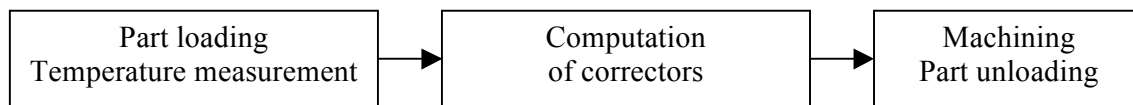| Part loading Temperature measurement | → | Computation of correctors | → | Machining Part unloading |
|---|---|---|---|---|

Figure 10.A shows an example of tool trajectory compensation when part is warmer than reference.

## 5      Method to take into account initial temperature of the part

*5.1. FEM Simulations*

Thermo mechanical effect of the machining of a brake disc is simulated using a commercial FEM $P_c = K_c \cdot A_d \cdot V_c$ to part represent 10% of power consumption for cutting. Power consumptions were estimated using a linearized Kienzle model with $K_c$ = 1100 MPa.

$$P_c = K_c \cdot A_d \cdot V_c \tag{5}$$

with $P_c$ the cutting power, $A_d$ the cutting section and $V_c$ the cutting speed.

Table 3 and figure 3 shows plan of procedure for finish machining of brake disc (second dry operation).

Hypotheses for FEM simulations are:
•      Material comportment is supposed linear and homogeneous
•      Material volume removed by process is weak compare to part volume (<3%). Simulations are done on finished part;
•      Heat flow is not dependant of tool position on part. For one type of operation, heat flow is constant (Battaglia *et al.* 2005);
•      Heat flow is imposed in one step all over machined surface (short duration of machining compare to duration of operation, Boyer *et al.* 2012);
•      No heat exchange between part and jaw (small contact surfaces);
•      Heat transfer coefficient (assumed constant):10 W/(m².K);
•      Part is clamped with a three-jaw chuck (Fig. 1).

Thermal and mechanical analyses are weakly coupled and are thus conducted successively. Table 3 compares thermal energy introduced in part to thermal losses by convection with environment. We remark that convection do not affect heat energy into part. For next analysis, if we just consider part during manufacturing heat convection could be neglected.

**Table 3**  Simplified plan of procedure for second operation

| | Operation | Heat flow W | Duration s | Thermal energy give to part J | Thermal energy variation into part J | Losses by convection with environment J |
|---|---|---|---|---|---|---|
| 1 | Finish turning face 2 | 2790 | 0,752 | 2098 | 2097 | 0,29 |
| 2 | | | 2,82 | | -1,17 | 1,17 |
| 3 | Rough cylinder 2 | 2995 | 3,063 | 9173 | 9170 | 2,97 |
| 4 | | | 1,328 | | -1,68 | 1,68 |
| 5 | Finish turning cylinder 1 | 500 | 0,224 | 112 | 111 | 0,28 |
| 6 | | | 3,044 | | -3,63 | 3,63 |
| 7 | ½ finish turning cylinder 2 | 750 | 2,969 | 2226 | 2222 | 4,00 |
| 8 | | | 1,225 | | -1,74 | 1,74 |
| 9 | Finish machining braking surfaces | 1170[1] | 7,256 | 8489 | 8474 | 14,95 |
| 10 | | | 4,903 | | -12,65 | 12,65 |
| 11 | Finish turning cylinder 2 | 405 | 0,497 | 201 | 199 | 1,30 |
| 12 | | | 7,217 | | -18,90 | 18,90 |
| 13 | Finish turning cylinder 3 | 400 | 3,601 | 1440 | 1430 | 9,88 |
| | **TOTAL** | | **38,899** | **23 741** | **23668** | **73,74** |

*(1):585 W on each breaking surface*

Figure 7 shows temperature of parts before finishing operation for cylinder 2. Heat flows and part geometry lead to an inhomogeneous repartition of temperature rise along

cylinder 2. On face 2 side, cylinder 2 is warm by face 2 finish machining; on face 1 side, there is thermal diffusion to rest of part.

**Figure 7** Simulation of part temperature rise before finishing cylinder 2
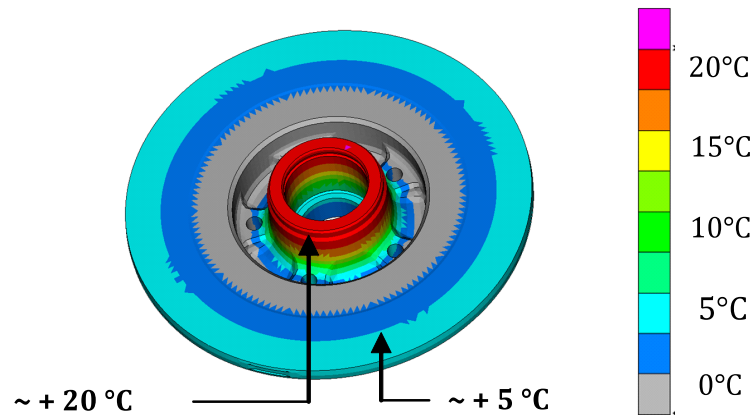


Simulated distortions during machining for cylinder 2 are represented on figure 8. Simulation shows a positive rapper of 4.5 between level 1 and 3 when finish machining of cylinder 2 starts. Temperature rise during manufacturing increases rapper of 4.5µm (hypothesis: 10% of power spindle is going to part). Machined parts measurement shows an average rapper increase of about 5 µm. To insure machined quality, it is necessary to cool parts or to take into account temperature rise of part during machining.

**Figure 8** Variation of diameter for cylinder 2 at 3 levels (Fig. 3) during second machining operation.
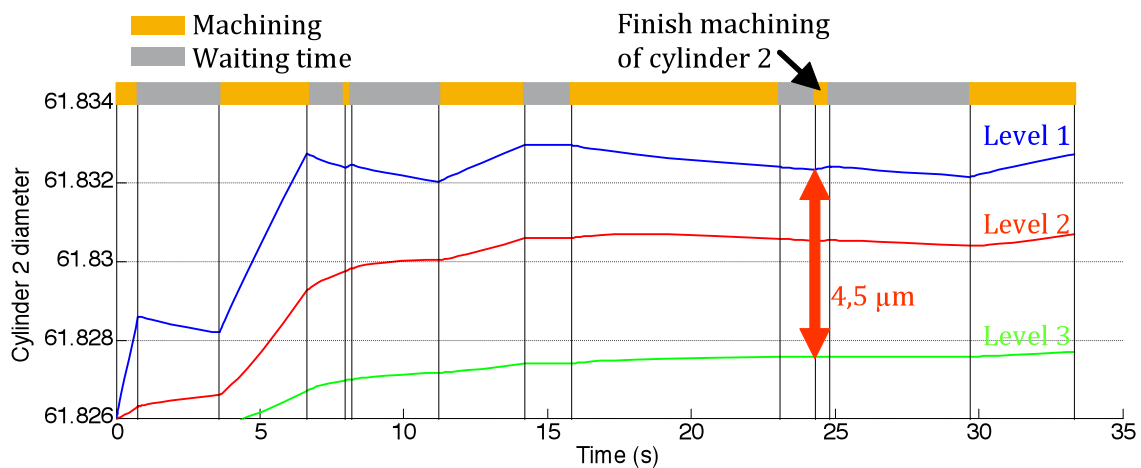


*5.2.   Correction implementation: temperature rise during machining*

Temperature rises of parts depends on many factors: temperature of workshop, tool wear, cutting conditions, material machinability, etc and there effects on tolerance could be important.

A solution to take into account this warm up to correct tool trajectories is to measure temperature of parts at loading and unloading at the same point. This measuring point has to be representative of temperature in the affected by distortions zone.

Correction for a part is done with measurements done on previous part. To avoid errors due to bad measurements or quick changes in temperature rise (tool failure, replacement of tool, change in work piece material structure, stop of the production line …) measuring process has to be supervised. Figure 9 and 10.B illustrate this solution.

Correction coefficient allows correction of machined cone. It is estimated with FEM simulations and has to be correlated to parts measurements.

**Figure 9** Correction implementation of part temperature rise
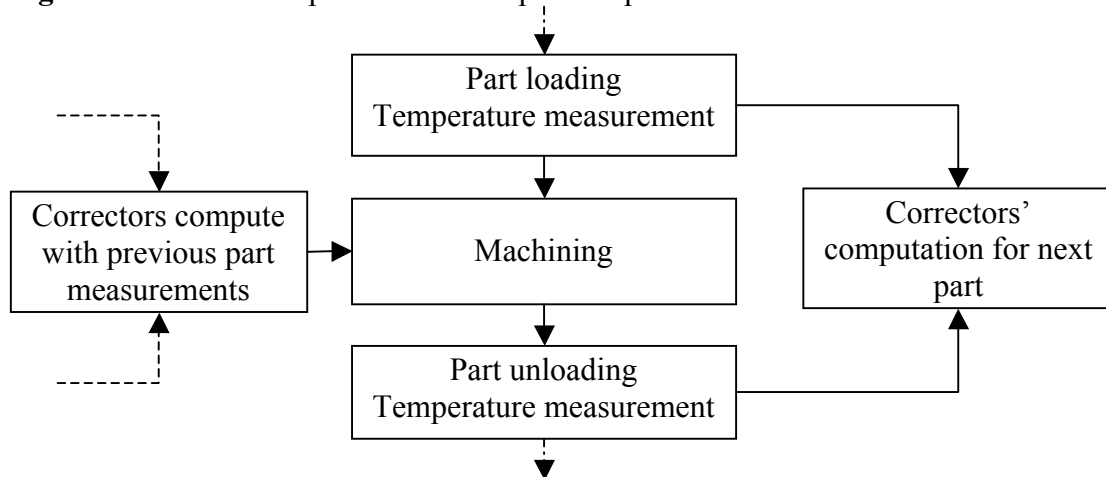


## 6    Conclusion

In first part, a method was proposed to identify machined characteristic sensible to workshop temperature. This method allows manufacturers (if standard deviation of the process has been evaluated) to predict if machining operations needs thermo regulation of parts temperature or thermal correction of tool trajectories.

**Figure 10** Tool trajectories with and without compensation



A. Compensation of part loading temperature

B. Compensation of part temperature increase during machining
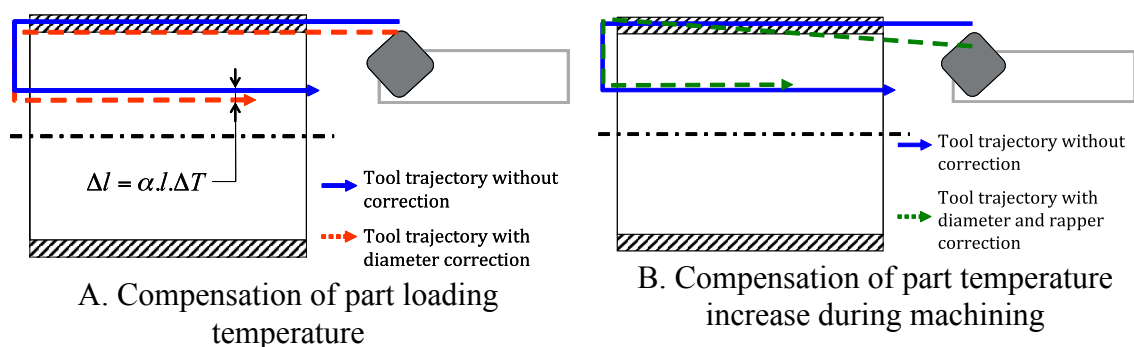
FEM simulation method, presented in second part, could help manufacturers to understand thermo mechanical distortions of parts during manufacturing. This method could not predict exactly distortions of parts during manufacturing. It just allows rapid

identification of order of magnitude for part temperature rise and distortions during machining. With this estimation, manufacturers could choose to do (or not) cooling of parts or thermal compensation during machining or could reorganize plan of procedure to minimize distortions.

Methods proposed were used to understand and solve thermo mechanical distortions problems in a cast iron brake disc dry machining line.  Future work will focus on optimizing the accuracy of heat flow.

## Acknowledgements

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