

# AN ANALYSIS OF THE CUTTING TEMPERATURE FOR THE TAPPING PROCESS USING THE TOOL-WORKPIECE THERMOCOUPLE METHOD

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**Abstract.** *Temperature measurement in machining is complex, with many limitations and restrictions and these are linked to the measurement method and the process in which it will be applied. Tapping is one of the processes that imposes the most restrictions and limitations on temperature measurement methods. The chip-tool interface temperature is important data to feed numerical models and also to help in the analysis of wear problems and breakage of the cutting tap. The objective of this work is to quantify the temperatures found in tapping as a function of some process variables (cutting speed, workpiece material and cutting fluid), to understand how influential these variables are in temperature, since there are no results in the literature for the threading process, and to show the advantages of adapting the tool-workpiece thermocouple method for the tapping process. The results show a 34% reduction in dry cutting temperature when compared to oil and emulsion conditions.*

**Keywords:** *Tapping, Cutting temperature, Tool-workpiece thermocouple, Internal threading, Calibration*

## 1. INTRODUCTION

Knowledge of machining temperatures is very important for understanding the various phenomena that occur during the process. Wear mechanisms, machining forces and surface integrity are directly linked to heat generation and temperature distribution. According to Abukhshim et al. (2006), the machining of metals is not completely understood due to the complexity and non-linearity between the phenomena of deformation and temperature.

The measurement of chip-tool interface temperature in processes with rotating tools is more complex and requires adjustments and adaptations of measurement methods. Patru et al. (2021), researched the specific energy and temperature of the chip-tool interface in the milling of aluminum alloys and for this purpose they inserted K-type thermocouples in the workpiece to be machined. Costa and Polli (2021), studied the effect of the penetration method in the turning of austenitic stainless steel AISI 304L threads and among the analyzes is the temperature, through infrared thermography. Ramesh et al. (2023), used a thermal camera to measure the temperature in the turning process in a titanium alloy (Ti6Al4V). Gonzalez et al. (2023), used thin-film sensors to measure temperature at the chip-tool interface. The objective was to obtain more accurate results at the expense of the short life of the sensors.

Figureiredo et al. (2022), present several methods to estimate the heat flux during machining and, for this purpose, present the most common temperature measurement methods, since this information, in several situations, feeds the numerical models. Mane et al. (2020), used a 2D model in FEM and observed that as the feed increased, the location of the maximum temperature approached the cutting edge. To compare the results, they measured temperature with an infrared camera. Over decades of research, various temperature measurement methods have been applied in machining and one that stood out was the tool-workpiece thermocouple method used by (Hebert, 1926; Braiden, 1968 And Lima et al., 2018).

The number of researches related to the tapping process has increased considerably. However, when evaluating by line of research, the number of studies is still unsatisfactory. To exemplify some currently researched lines, we can highlight works such as Ma et al. (2019), they were the pioneers in publishing an article addressing the dynamic problem in the tapping process. Martins et al. (2022), and Barooah et al. (2020), investigated wear in the tapping. Gil Del Val et al. (2020), analyzed the effect of coating on the life of the cutting tap and Steininger et al., (2015), analyzed the effect of coating on adhesion during tapping of a hypereutectic Al-Si alloy. Dogrusadik et al. (2021), and Polvorosa et al. (2020),

studied the tapping in titanium and nickel superalloys. Gil Del Val et al. (2023), studied the effect of a thermal gradient in the rake face in the surface residual stresses when tapping at high-speed cutting conditions. Fernandes-Lucio et al. (2023), developed a new tool holder capable to reduce the lack of synchronization improving 20% the tool life.

These works highlight the different lines of research in tapping and their importance, but it is still not possible to observe, as in other processes, a line of research that stands out, with temperature being one of the areas that most suffers from the lack of published papers. Pereira et al. (2020), investigated the temperature of the chip-tool interface fillet by fillet, in the conical part, through the tool-workpiece thermocouple. Tanaka et al. (2013), measured the chip-tool interface temperature using a two-color fiber-optic pyrometer. These two works are pioneers in the methods and results presented in temperature measurement in the tapping process.

One of the objectives of this work is to quantify the effect of threading process variables on the chip-tool interface temperature, also to understand how influential these variables are on temperature and to understand the advantages and disadvantages of the tool-workpiece thermocouple method applied to the tapping. There is rare research on temperature in tapping with a cut tap which greatly limited the bibliographic review, this makes clear the importance of works like this one, which add temperature values to the process and show whether the effect of process variables is more or less influential in tapping.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

For the tapping tests, Gray Cast Iron GG30, SAE 1045 steel and titanium alloy Ti-6Al-4V were used, with Gray Cast Iron being the base material for comparisons and main variations. Due to the geometric characteristics of the materials, the specimens do not have the same dimension from one material to the other, the dimensions of the cast iron specimen were 30 x 32x 32 mm and for the dry test with cast iron the length was 15 mm to prevent premature cut tap failure. The tool used for tests was an HSS-E M10X1.5 cutting tap, without coating, with three flutes, helical tip and four fillets in the conical part.

### **2.2 Experimental procedure**

The tests were carried out in a machining center (power of 15kW and maximum speed of 7500 rpm). The cutting conditions correspond to the range indicated by the manufacturer for Gray Cast Iron and the other materials followed the conditions for comparison. For each evaluated condition, three tests were performed and the taps machined no more than 3 samples. In addition to the material of the specimens, the other variables were cutting speed (10, 30, 50 m/min) and cutting fluid (dry, emulsion and oil). The experiments were carried out with one test and two replicates for each cutting condition tested.

Figure 1 shows the setup for signal acquisition during the tapping test. It is possible to notice a contact pin with the cut tap, the pin is a tap that was cut to make contact with the tool and the extension cable (copper wires) comes out of it to the multimeter and the other extension cable comes out of the workpiece. The insulation of the part was made with a polymer and the tool was isolated through epoxy painting on the Morse cone, the insulation serves to avoid external interference in the electromotive force (e.m.f). For the acquisition of e.m.f. and temperature during calibration, a Keysight Technologies Agilent model 34970A acquisition unit and BenchLink Data Logger Pro software were used. The acquisition rate was 14.3Hz, contemplating the tapping time for a cutting speed of 50m/min, since the cutting time at this speed is approximately 630 milliseconds.

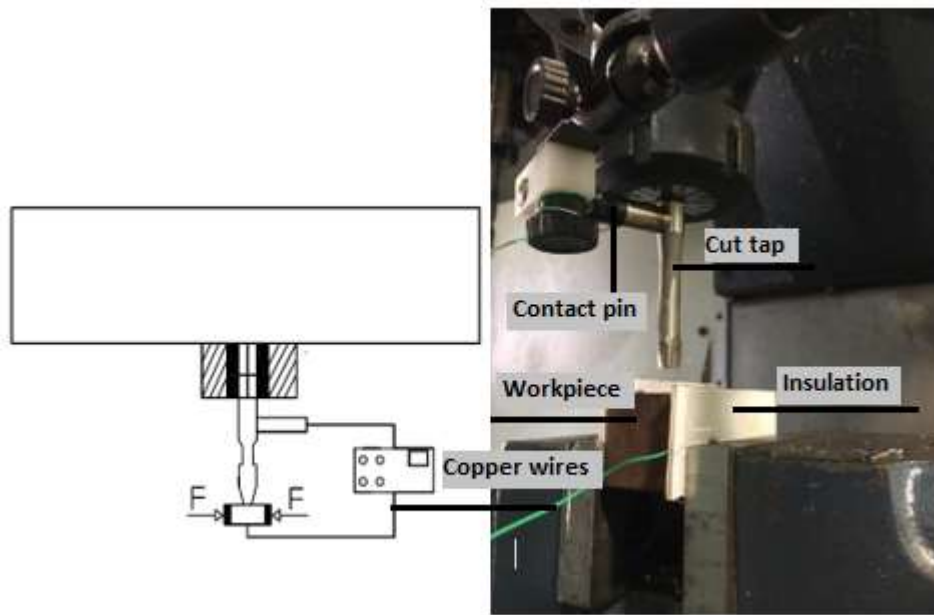


Figure 1. Assembly for tapping tests

### 2.3 Tool-workpiece thermocouple calibration

Calibration of the tool-workpiece thermocouple is a critical point in researches that use the tool-workpiece thermocouple method. The calibration of the set with Gray Cast Iron as part material was in a slow transient regime (Fig. 2), it was decided to use an oxyacetylene torch as a heat source and the heat was applied to a transition pin between the tap and the workpiece, made of same material as the part, following the same method as Pereira et al. (2020), uses in his work. Known Type K thermocouples were used to acquire the temperature simultaneously with the acquisition of the e.m.f generated in the tool-workpiece thermocouple. The K-type thermocouple was placed in contact between the pin (part material) and the tap, thus the temperature values measured during calibration represent the chip-tool interface temperature.

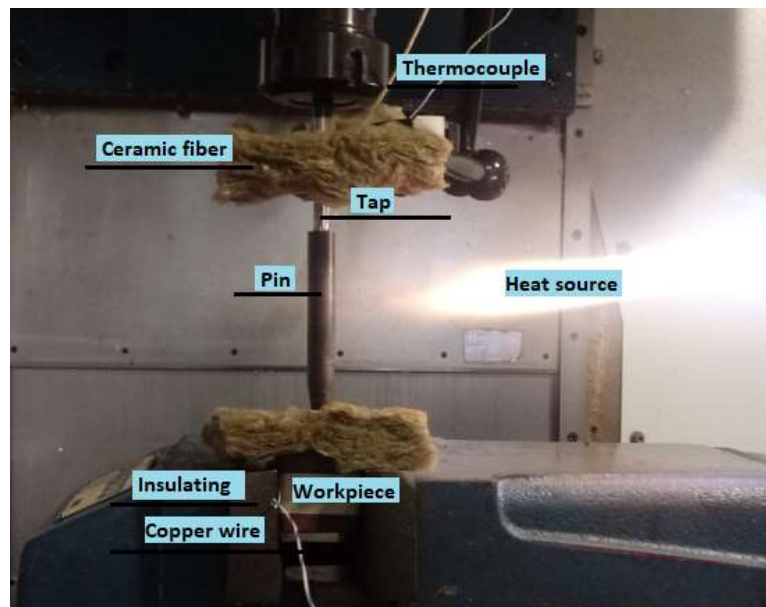


Figure 2. Assembly for calibration of Gray Cast Iron

The calibrations of the SAE 1045 steel and the titanium alloy Ti-6Al-4V were carried out in a steady state (Fig. 3), in a muffle furnace with a maximum temperature of 1200°C. Gray Cast Iron was not calibrated in the furnace, due to the difficulty of producing a long sample (simulating the chip). The calibration method was based on the work of Cunha (2020), and adapted for threading. Assembly with a long tool was carried out using several identical taps joined together 295mm of length, a long chip approximately 1000mm length of SAE 1045 and Ti-6Al-4V have been produced. One end of the tool was joined to one end of the chip and this union was placed inside the furnace and extension wires were

connected to the other end of the tool and the chip to connect the tool and the chip to the multimeter. It is important to point out that the tool and the chip are long so that at the end with the extension wire the temperature remains close to the ambient temperature, thus not forming a new thermocouple.

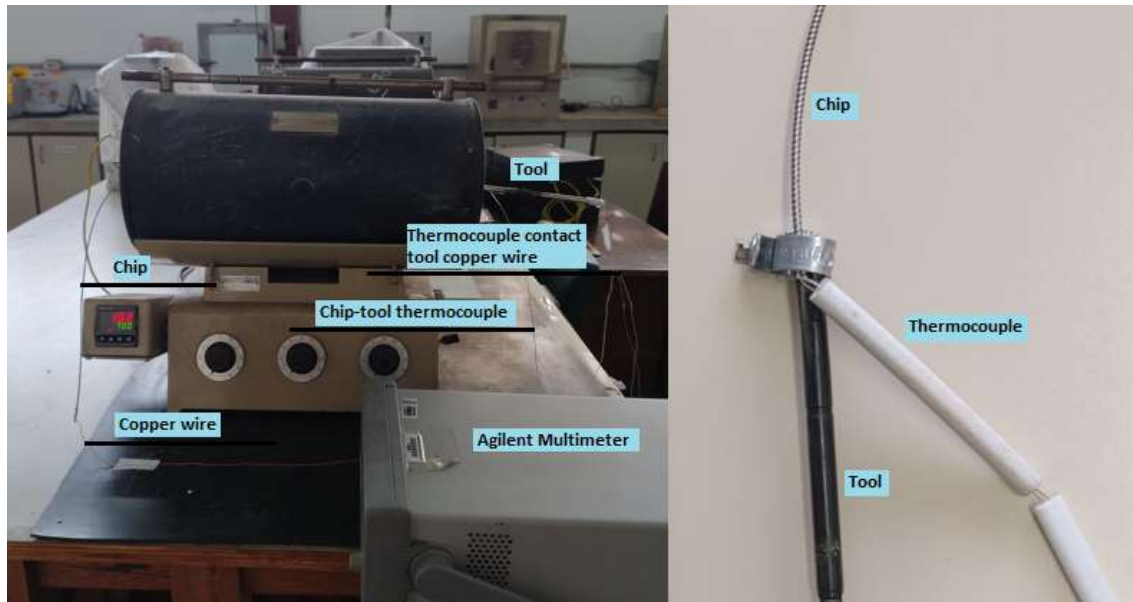


Figure 3. Assembly for calibration of SAE 1045 steel and Ti-6Al-4V titanium alloy and contact chip-tool for calibration

The thermocouple for reading the chip-tool interface temperature, during calibration in the furnace, was welded close to the contact, as shown in Fig. 3. A thermocouple was placed close to the extension wire tool contact, to ensure that the temperature did not undergo considerable changes ( $\pm 5^\circ\text{C}$ ). The acquisition rate used for calibrations with oxyacetylene flame and in the furnace was 6.6 and 2Hz respectively, since the calibration time in the transient state is shorter than in the steady state.

Figure 4 shows the gray cast iron calibration curve with its respective coefficient of determination. Remembering that the curve of this material was made in transient regime. The maximum temperature values reached during the calibration, approximately  $700^\circ\text{C}$ , ensure representativeness during any cutting condition used in this work. This type of calibration has a major limitation in relation to the maximum temperature, because it is extremely difficult for the heat conducted by the pin to the workpiece-tool contact to cause the temperatures at this point to exceed  $700^\circ\text{C}$ , Kaminise et al. (2014), development of a tool-work thermocouple calibration system and obtained maximum temperatures close to  $800^\circ\text{C}$ , but one of the challenges and objective of the work was compensation due to the increase in temperature in the extension wire tool contact.

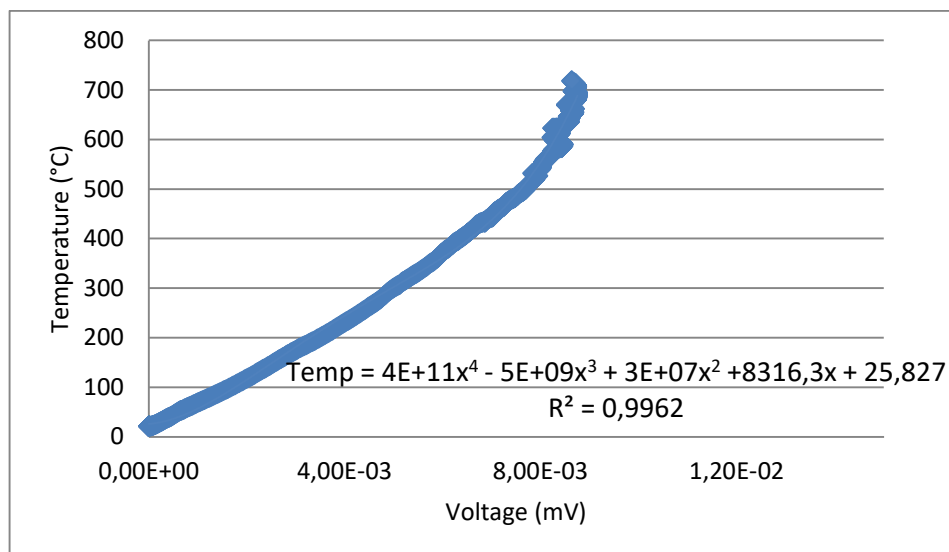


Figure 4. Gray Cast Iron calibration curve

Figure 5 shows the calibration curve of the Ti-6Al-4V titanium alloy with its respective coefficient of determination. Remembering that the curve of this material was made in steady state. Calibration in a furnace does not have the same temperature limitations as calibration with an oxyacetylene flame, but the programmed temperature was 650°C, as the process would not reach higher temperatures. In this type of calibration, the limitations are associated with the type of fixation of the hot joint. and oxidation of the tool material.

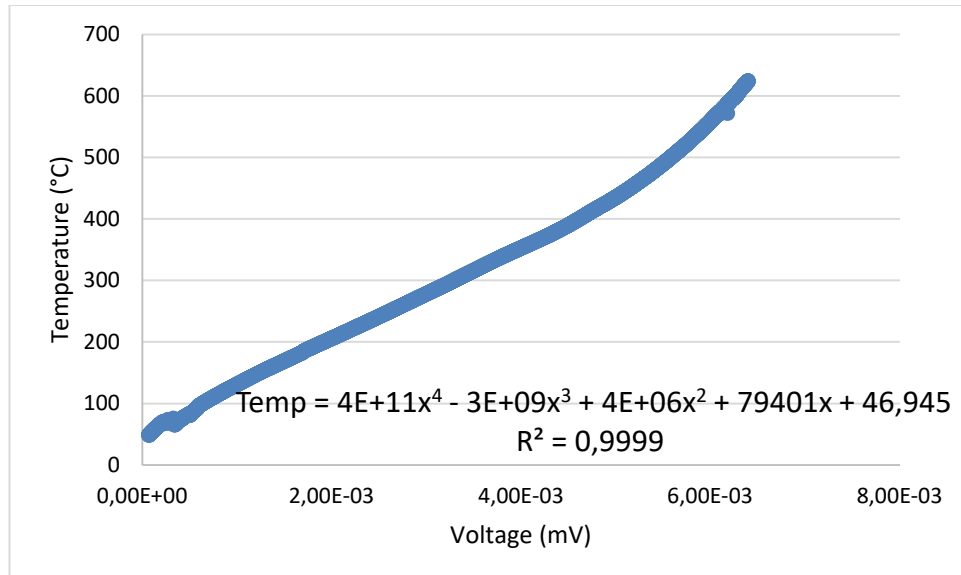


Figure 5. Ti-6Al-4V calibration curve

Figure 6 shows, respectively, the SAE 1045 steel calibration curve and their respective equations and determination coefficients, with the value close to 1 for both curves. These two curves were obtained through steady state, however, for the SAE 1045 steel there was an anomaly that makes curve fitting difficult. The curve was divided into phases 1 and 2, red line separating the phases, this division was necessary due to the difficulty in performing a single satisfactory curve fit. Due to the anomaly presented by the SAE 1045 steel calibration curve, the furnace tests were repeated in a transient regime, using an oxyacetylene torch as a heat source, and similar results were obtained, which proves that the anomaly is a characteristic of the combination of HSS with SAE 1045 steel.

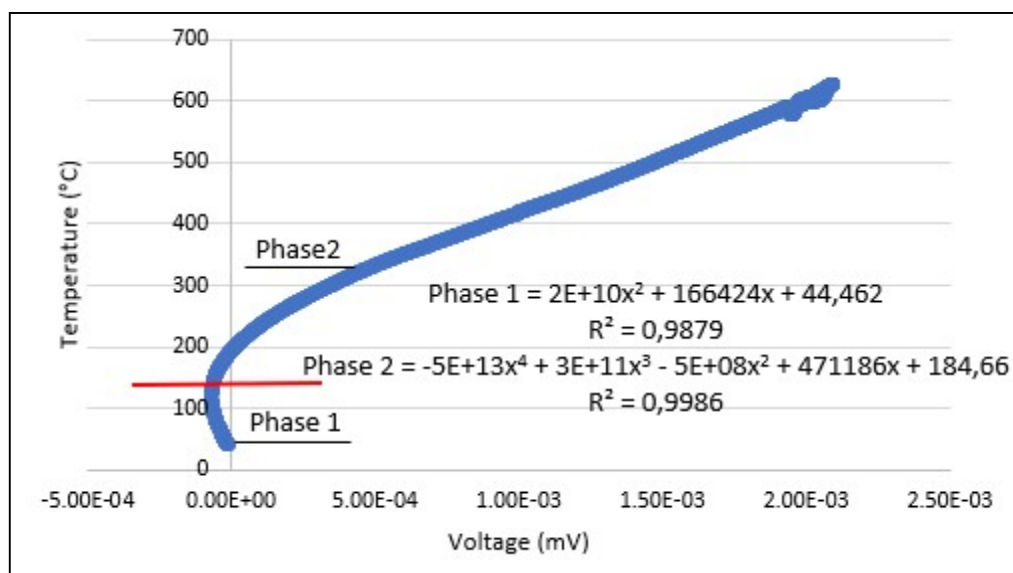


Figure 6. Calibration curve and equations for each phase for SAE 1045 steel

### 3. RESULTS AND DISCUSSIONS

The temperature over time signal shown in Figure 7 is the signal collected in the tapping test, after converting the e.m.f. into temperature. The part circled in red is the thread cutting region and with this data the average temperature values shown in Figs 8, 9 and 10 are calculated. The return temperature is close to 50°C, this shows the efficiency of the fluid in reducing friction and reducing material adhering to the tap and thread. In their work Pereira et al. (2020), show a similar return temperature to the cutting region without the use of cutting fluid.

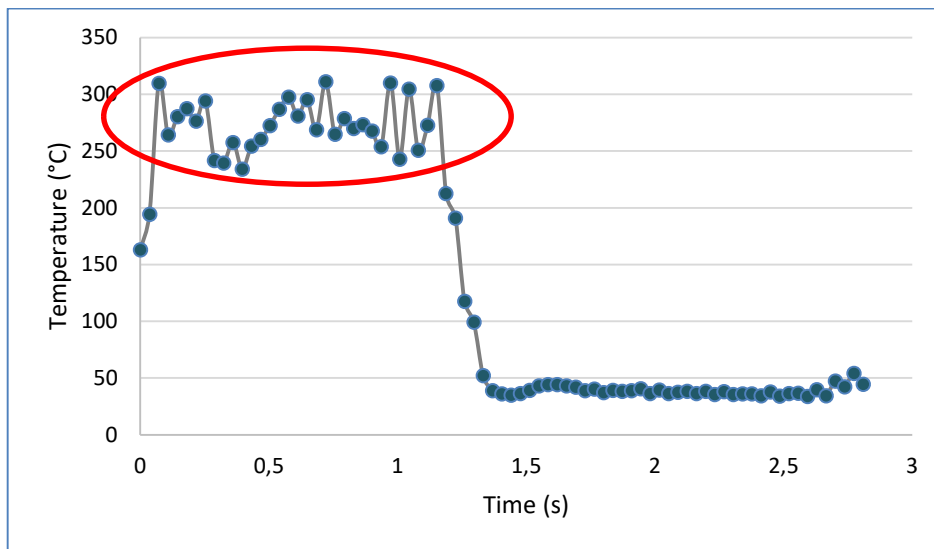


Figure 7. Temperatura no rosqueamento do Ferro Fundido Cinzento com velocidade de 30m/min e emulsão

Figure 8 shows the behavior of the chip-tool interface temperature during gray cast iron tapping, with emulsion and 3 different cutting speeds. The behavior of cutting temperature as a function of cutting speed is known, the results help to understand the problems that lead to the end of life and/or failure of cutting taps. Cutting speeds of 30 and 50m/min are not commonly used, but are within the range recommended by the manufacturer, and at 10m/min tool temperatures are low, even for HSS, which shows that the temperature has few influences on wear.



Figure 8. Behavior of chip-tool interface temperature as a function of cutting speed for tapping, calculated using Gray Cast Iron calibration curve

It is possible to observe in Figure 9 the behavior of the temperature along the tapping of Cast Iron at 30m/min in 3 different cutting fluid conditions: dry, emulsion, integral oil. The two fluid conditions were virtually identical in temperature reduction which does not mean they will have the same effect on wear. The dry condition causes the temperature to increase by almost 150 °C, compared to the fluid conditions, this demonstrates how sensitive the process is to the use of cutting fluid and the temperature reduction is observed with the application of emulsion and oil, this also

indicates that a very important source of heat in the tapping is friction, since even with new tools, better friction conditions, the reduction was considerable (34%).

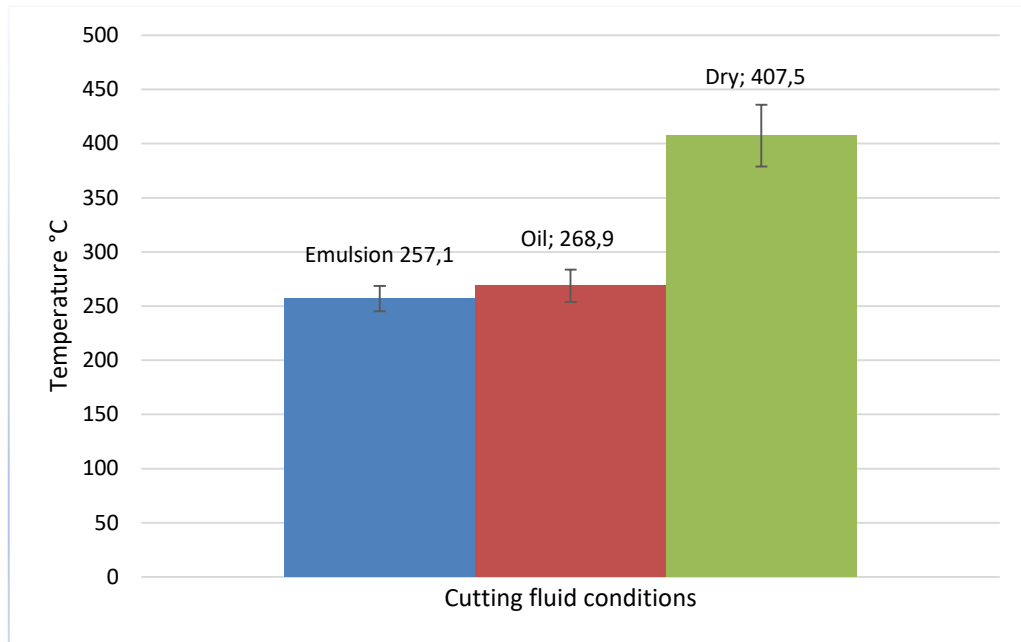


Figure 9. Comparison of chip-tool interface temperature with different lubrication/cooling conditions, calculated using Gray Cast Iron calibration curve

Another analysis carried out was in relation to the workpiece material (Fig. 10), it is possible to observe that gray cast iron and SAE 1045 obtained similar temperatures, while the titanium alloy was 30% higher than the other two. This fact is associated with greater mechanical strength, greater hardness and low thermal conductivity when compared to the other two materials. The cutting fluid condition for these tests was the emulsion.

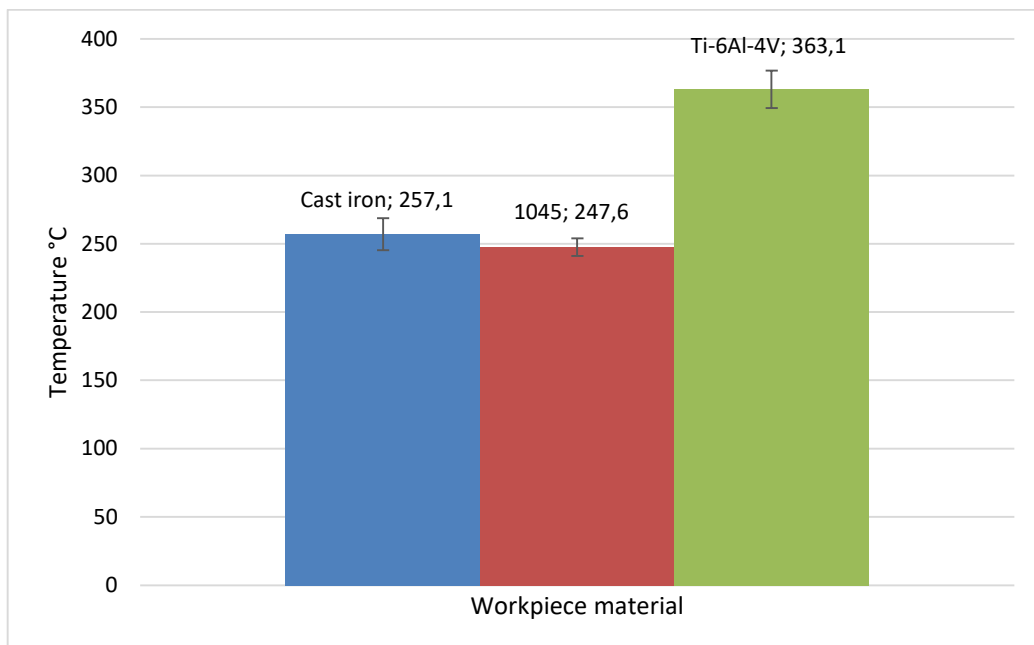


Figure 10. Comparison of chip-tool interface temperature with different workpiece materials

Tanaka et al. (2013), evaluated two materials in similar situations in the tapping, AISI 1045-BN steel and AISI 303 stainless steel. The interface temperature was measured with a two-color pyrometer and with this sensor the measurement is made edge by edge, in an instant of exposure, and thus the temperature on the exit surface can be measured. Cutting speeds ranged from 20 to 30m/min and the temperatures obtained at the highest speed for AISI 1045-BN steel were approximately 270°C and 380°C for AISI 303, with the application of lubricating oil. The temperatures were a little higher

in the Tanaka et al. (2013), as they used oil to lubricate the tap before tapping and in this work, emulsion was used during tapping and, as shown in Fig. 9, emulsions reach slightly lower temperatures than oils. These similarities show how the two measurement methods are satisfactory in measuring the chip-tool interface temperature.

#### 4. CONCLUSION

In this work, the tool-workpiece thermocouple method was applied to measure the chip-tool interface temperature in the tapping process as a function of cutting speed, type of cutting fluid and workpiece material.

The calibration in transient and steady state showed a coefficient of determination above 0.987, which proved a high correlation between the curve and the equation. For SAE 1045 steel, the curve showed an anomaly for temperatures below 200 °C, approximately, the e.f.m started negative and then became positive.

In relation to the fluid used, the conditions with application of emulsion and oil obtained a lower temperature than the dry one. When comparing the temperature results with the application of emulsion and oil, the results are very close, but the value of the emulsion was slightly lower.

The last analysis was in relation to the material of the piece, with Ti-6Al-4V having the highest temperatures, approximately 30% higher than the other two. SAE 1045 steel and gray cast iron had practically identical temperature results.

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## 7. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this work.