CORRELATION BETWEEN LEIDENFROST TEMPERATURE, COOLING CAPACITY AND MACHINING TEMPERATURE: AN EXPERIMENTAL STUDY OF CUTTING FLUIDS

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ABSTRACT

Much of the energy consumed by machining materials is converted into heat, which causes several technical and economic problems for the process. The cutting fluid application by the conventional method forms a vapor film of low thermal conductivity, which prevents direct contact between the fluid and the heated surface; the so-called Leidenfrost effect, which reduces cooling efficiency. Studies of this phenomenon applied to the machining of materials are still very restricted and scarce. In this sense, the present work experimentally studied the correlation of parameters Leidenfrost temperature, cooling capacity and machining temperatures, applied to the SAE 52100 steel turning process with conventional lubri-coolant, with different cutting fluids. The thermal properties of the studied cutting fluids were taken from the technical-scientific literature. An experimental apparatus was developed for measuring and acquiring machining temperatures. Synthetic cutting fluids were shown to have a better cooling capacity, followed by semi-synthetic fluids and emulsions. There is no relationship between Leidenfrost temperature, cooling capacity, and machining temperatures for the different types of cutting fluids studied.

Keywords: Leidenfrost effect, cutting fluids, machining temperature, turning, SAE 52100

NOMENCLATURE

a_p	depth of cut, mm
D_f	final machined diameter, mm
D_i	initial machined diameter, mm
f	feed rate, mm/rev
l_f	feed length, mm
l_u	cutting length, mm
LFT	Leidenfrost temperature, ºC
n	spindle speed, rpm
t	machining time, s
$t_{cooling}$	cooling time, s

INTRODUCTION

Leidenfrost (1966) first identified, in 1756, the phenomenon of film boiling, which was later called the "Leidenfrost Effect". This phenomenon is characterized by forming a low thermal conductivity vapor film, which covers the heated surface and prevents direct contact with the liquid; reducing the convection heat transfer coefficient and the efficiency of the surface cooling process.

Nukiyama (1934) and Drew and Mueller (1937) identified the different boiling regimes in saturated water at 1 atm; with the empirical characterization of the Leidenfrost point as the beginning of the film boiling regime and with minimal surface heat flux.

The existence of a "Leidenfrost film" in machining was exposed by Jäger et al. (2016) during the analysis of flank wear in lubri-coolant forced application. Su et al. (2016) demonstrate that lubri-coolant application (compared to conventional and dry methods) is more efficient because it breaks the "Leidenfrost film", allowing the cutting fluid to contact the surface of the tool's cutting edge and reducing flank wear. The studies by Behera et al. (2017a) and Behera et al. (2017b) showed that lubri-coolant application with nanoparticles reduces tool wear and cutting forces; since nanoparticles tend to break the vapor layer, eliminating the Leidenfrost effect and increasing the cooling rate.

Alagan et al. (2018) minimized the Leidenfrost effect by employing inserts with textured surfaces. Kim et al. (2011) and Kim et al. (2012) justified that texturing acts as a nanoporous surface, increasing the Leidenfrost temperature (LFT). Alagan et al. (2020) showed that the Leidenfrost effect can lead to the appearance of cavitation "pits" on the flank surface of cutting tools.

In the application of analytical methods for predicting Leidenfrost temperature, the works by Spiegler et al. (1963), Baumeister and Simon (1973), and Wang et al. (2020) stand out. In the experimental determination of Leidenfrost temperature, the following works stand out: A) Bernardin and Mudawar (1999), reporting the increase in experimental discrepancies due to the influence of several physical parameters (such as the fluid density, deposition method, thermal properties, surface finish and presence of impurities) and B) Ouattara (2009), in the demonstration, through comparative cooling curves between pure water and emulsion, that the Leidenfrost point is delimited by the boundary between transition and boiling film.

Huang and Caray (2007) and Mohapatra et al. (2014) observed that adding salts – such as NaCl, KCl, and $MgSO_4$ – increases the surface tension and destabilizes the vapor film, increasing the Leidenfrost temperature. Pati et al. (2018) show that emulsions (composed of water, surfactants, and oil) present a reduction in the contact angle and surface tension due to the presence of surfactants, with minimization of the Leidenfrost effect by the partial condensation of steam due to oil. Arena (2019) determined the cooling curves for cutting fluids types – emulsion, synthetic and semi-synthetic, and in different water concentrations – with analysis and identification of boiling regimes, time and cooling capacity and Leidenfrost point.

This work aims to evaluate, and experimentally validate, the correlation of parameters: Leidenfrost temperature, cooling capacity, and machining temperatures for different cutting fluids – emulsion, synthetic and semi-synthetic, and in different concentrations – applied to the turning process of the SAE 52100 steel with conventional lubri-coolant.

MATERIALS AND METHODS

This work deals with the study and experimental validation of the influence of Leidenfrost point on the cooling capacity of different cutting fluids, applied to the external cylindrical turning process of SAE 52100 steel under conditions of high cutting speed.

The cutting fluids studied, from the same manufacturers and physical conditions as Arena (2019), are shown in Table 1.

Table 1. Characteristics of the cutting fluids used.

Cutting Fluid	Concentration in Water [%]	Test Identification
Soluble Emulsion A, manufacturer LUCHETTI	2.50	EM-2.5
	5.00	EM-5
	10.00	EM-10
Synthetic, C270CG, manufacturer TRIM	4.00	SI-4
	7.00	SI-7
	10.00	SI-10
Semi-synthetic, manufacturer DECORVIT	1.25	SS-1.25
	2.50	SS-2.5
	5.00	SS-5

The turning process occurred in a universal lathe Magnum Cut, FEL-1440 GWM model, spindle speed $n = 1800\ \text{rpm}$ and cutting parameters $a_p = 0.8\ \text{mm}$ and $f = 0.19\ \text{mm/rev}$. The cutting fluid was applied at the tool-material interface by a low-pressure lubri-coolant system with a flow rate of 1.0 l/min.

The sample were manufactured from SAE 52100 steel tube and according to ASTM A295/A295M-14 standard. Figure 1 schematically illustrates the machining process of samples, in real dimensions and machining parameters.

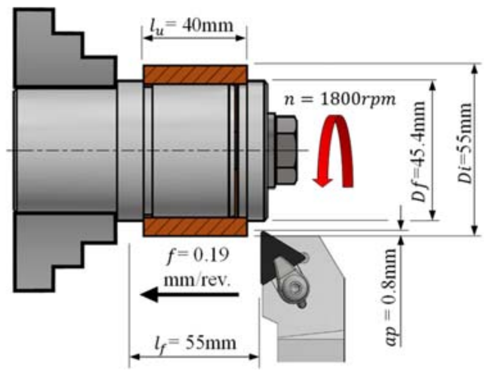

Figure 1. Machining scheme of samples.

The machining time for each pass, depending on the length of the sample, is calculated using the Equation:

$$t = \frac{60.l_u}{n.f} \tag{1}$$

Of the parameters used, there is a machining time of 7.02s per pass. In each test were performed six (06) passes, totaling 42.12s per test. At the end of the passes, the cutting edge is replaced at the end of each test.

The heat flux produced by the deformation rate of the removed material and the friction in the contact area between the chip and the tool is conducted through the cutting tool. The measurement of temperatures takes place through a type K micro thermocouple, made of Nickel-Chrome (+) and Nickel-Aluminum (-), with a diameter of 0.3 mm and tolerance of ±1.5°C for the range of working temperature from - 40ºC to 333ºC. The thermocouple was placed in the tool holder, between the shim and the underside of the insert tip, as shown in Figures 2 (a) and (b). Temperature data acquisition was performed using a data logger, model TC-08 from Pico Technology, with an acquisition frequency of 1 Hz and connected to a computer via a USB cable; as shown in Figure 2(c).

Three (03) tests were performed for each different type of cutting fluid studied, totaling twenty-seven (27) tests. Figure 3 illustrates the experimental procedure used for machining, measuring, and acquiring temperatures in a summarized schematic form.

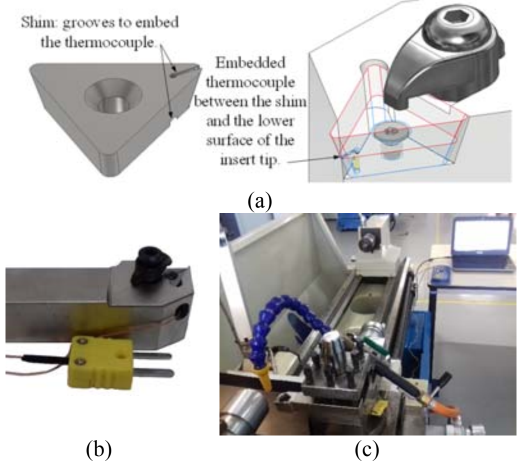

Figure 2. (a) Adaptation of the insert shim for insertion of the thermocouple, (b) mounting the thermocouple in the tool holder, and (c) temperature acquisition system.

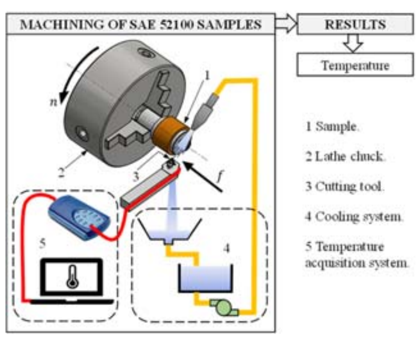

Figure 3. Schematic assembly of the experimental apparatus.

RESULTS AND DISCUSSION

Plotting the average machining temperature curves for the emulsion and synthetic cutting fluids, we have, in that order, Figures 4 and 5

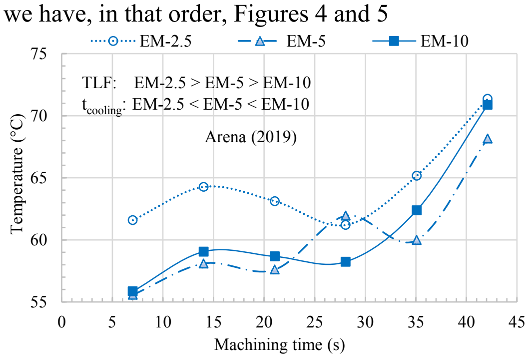

Figure 4. Machining temperatures (Emulsions – 2.5%, 5% e 10%).

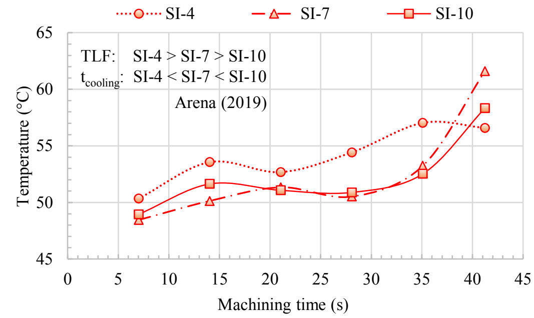

Figure 5. Machining temperatures (Synthetic Fluids – 2.5%, 5% e 10%).

. Highlighting the presence, in the graphs, of the classification of fluids regarding the Leidenfrost temperature and the cooling time, according to experimental data from Arena (2019).

The results in Figure 4 show that the EM-2.5 had higher machining temperatures, despite the higher LFT and higher cooling capacity. However, the EM-5 - with greater cooling capacity and LFT than EM-10 - presented slightly lower machining temperatures.

From Figure 5, it can be seen that the cutting fluid SI-4, practically during the entire test, presented higher temperatures than the fluids SI-7 and SI-10; although it has the greater cooling capacity and higher LFT among synthetic fluids. In turn, the SI-7 fluid, which has a greater cooling capacity and LFT than SI-10, presented slightly lower machining temperatures during the first part of the test.

Thus, it is not possible to say precisely that emulsion and synthetic fluids, with higher LFT, also have the better cooling capacity in the SAE 52100 steel turning process. This conclusion is justified by the lack of an evident correlation between the parameters LFT, cooling time and machining temperatures for these types of cutting fluids.

Figure 6 shows the average curves of machining temperatures for semi-synthetic cutting fluids, highlighting again the presence of Arena (2019) data in the graph presented.

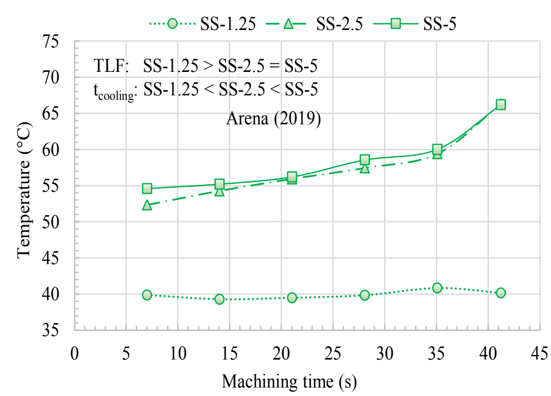

Figure 6. Machining temperatures (Semi-synthetic fluids – 1.25%, 2.5% e 5%).

From the results in Figure 6, it is possible to state a correlation between LFT, cooling time and machining temperatures for the semi-synthetic fluids studied. It was found that semi-synthetic fluids with higher LFT also have better cooling capacity in the SAE 52100 steel turning process; especially SS-1.25 fluid, due to its lower water concentration.

Synthesizing the results of Figures 4 to 6 in a single graph, plotting the respective standard deviation of each curve, we have Figure 7.

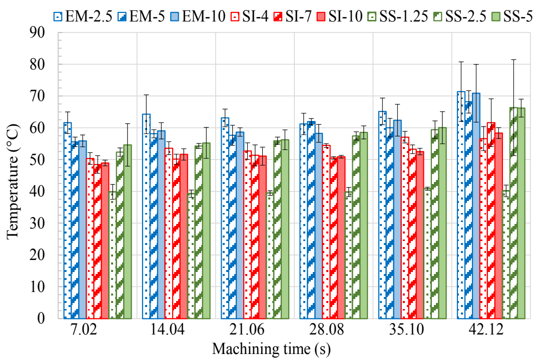

Figure 7. Machining temperatures for the different cutting fluids studied.

The results show, in its totality, that the synthetic cutting fluids presented better cooling capacity in the turning of SAE 52100 steel, followed by the semi-synthetic fluids and emulsions. An exception is the SS-1.25 fluid, which reached the lowest temperature in relation to the others due to the large presence of water in the mixture, which increased its thermal conductivity and, consequently, its cooling capacity.

Even with the reduction of the cutting speed at each turning pass, it was verified that the machining temperature increased with time for all types and concentrations of the used fluids. The temperature rise occurred due to the progression of wear on the cutting edge, producing greater friction at the material-tool-chip interface, increasing heat generation.

The large variation in temperatures, indicated by the standard deviation bars and with greater intensity at the end of the tests, is justified by the accelerated wear of the cutting tool in this situation, increasing heat generation.

Assuming that tool wear does not significantly influence temperatures at the beginning of the machining process, there is an analysis of the machining temperature curves for the first 02 passes; which is plotted in Figure 8.

The emulsions had the highest average temperatures in the range of 14 s, equal to 64.4°C for EM-2.5, 58.8°C for EM-10 and 58.5°C for EM-5. In the intermediate range, semi-synthetic fluids had mean temperatures equal to 56.3°C for SS-5 and 54.4°C for SS-2.5. Synthetic and semi-synthetic fluids of lower concentration had the lowest average temperatures, equal to 53.1°C for SI-4, 51.0°C for SI-10, 50.1°C for SI-7 and 40.0°C for SS-1.25.

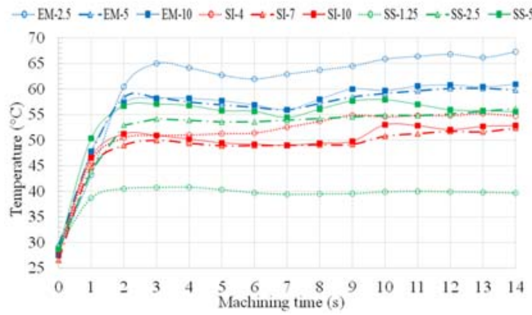

Figure 8. Initial machining temperatures.

The emulsions had the highest average temperatures in the range of 14 s, equal to 64.4°C for EM-2.5, 58.8°C for EM-10 and 58.5°C for EM-5. In the intermediate range, semi-synthetic fluids had mean temperatures equal to 56.3°C for SS-5 and 54.4°C for SS-2.5. Synthetic and semi-synthetic fluids of lower concentration had the lowest average temperatures, equal to 53.1°C for SI-4, 51.0°C for SI-10, 50.1°C for SI-7 and 40.0°C for SS-1.25.

Because of these results, it is possible to evaluate the relation of the average initial machining temperature (measured between 2 and 14 s), the LFT and the cooling time of the various cutting fluids studied, according to data from Arena (2019). Figure 9 graphically shows this comparison.

It was verified that there is no relationship between LFT and the cooling capacity of different cutting fluids studied. The results found that:

- Emulsions with higher LFT had higher average machining temperatures;
- Synthetic fluids with intermediate LFT had the lowest average machining temperatures;
- Semi-synthetic fluids with lower LFT had average intermediate machining temperatures.

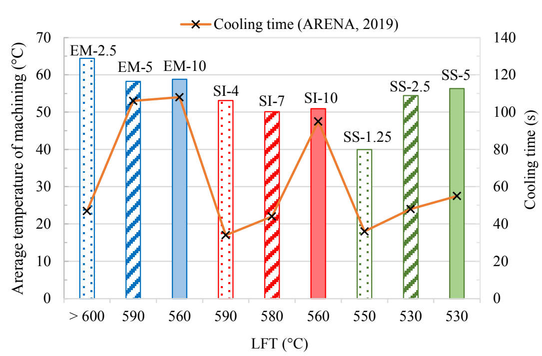

Figure 9. Correlation between average initial machining temperature, LFT and cooling time.

Under conditions of fluids of different types, but with the same or similar LFT, the EM-5 resulted in a machining temperature 10% higher than the SI-4, while the EM-10 resulted in a machining temperature 15% higher than the SI-10.

The greater cooling capacity in machining, associated with the higher Leidenfrost temperature, was only evidenced for semi-synthetic fluids. It was found that the lower the fluid concentration, the higher the LFT, the higher the cooling capacity and the higher the average machining temperature.

Conversely, emulsions and synthetic fluids, at the lowest concentrations – specifically EM-2.5 and SI-4 – did not show a relationship between higher LFT, better cooling capacity and the average machining temperature. The probable cause for higher average machining temperatures for these concentrations may be explained by the greater friction resulting from the low lubricating action of the solutions.

When performing the comparative analysis between the different types of cutting fluids, it can be stated that there is no correlation between the LFT and the machining temperatures obtained. The possible justification for this effect is the difference in thermal conductivity between the different cutting fluids studied.

Finally, there is no exact relationship between the cooling capacity of the cutting fluids - according to the experimental results of Arena (2019) - with the temperatures obtained in the machining tests of the respective fluids, since the heat generation differs between the experiments.

CONCLUSIONS

The behavior of different types of cutting fluids, classified by Leidenfrost point, was investigated in the external cylindrical turning process of SAE 52100 steel with lubri-coolant conventional. Machining temperatures were compared with LFT and the cooling capacity of the same types of cutting fluids, obtained experimentally on an Arena test bench (2019).

The results showed, in its totality, that synthetic cutting fluids had better cooling capacity, followed by semi-synthetic fluids and emulsions. Similar to the experiments made on a bench, it was shown that there is no relationship between the LFT and the cooling capacity during machining between the different types of cutting fluids studied. This conclusion is empirically justified because fluids with the same or similar LFT showed differences in machining temperature in the order of 10 to 15%.

According to experiments carried out on the bench, the lower concentration of the fluid increases the LFT and consequently the cooling capacity. In this study, however, this characteristic was only found in semi-synthetic fluids; which may be associated with lower water concentrations than emulsions and synthetic fluids.

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