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UNIVARIATE CUTTING FORCES ANALYSIS OF A NOVEL INTERNALLY COOLED TOOL DURING CAST GRAY IRON TURNING

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Abstract. *In this work, a new innovative technique was proposed using the concept of Internally Cooled Tool – ICT with a closed-loop, i.e., without any fluid dispersion to the atmosphere. A study was carried out on the behavior of ICT carbide tools during the turning of Cast Gray Iron – CGI made by Continuous Casting. The cutting forces were chosen as the output response variable to understand this behavior using this novel ICT technique. The input variables were ambient (Cutting Fluids in Abundance – CFA and ICT), cutting speed (40, 60, 80, 100, 120, 160, 200, 240, 360, 480 and 600 m/min). The depth of cut (doc) and feed (f) were kept constant at 1.0 mm and 0.1 mm/rot, respectively. The main findings were that cutting forces were higher in all conditions for ICT due to its exceptional cooling capacity that acts removing heat from the cutting zone, reducing the temperature and the material softening effect, and the poor lubricating capacity that turns chip difficult to remove. It is a complementary study of previously published ICT techniques.*

Keywords: *Internally Cooled Tools - ICT, Sustainable manufacturing processes, Cast Gray Iron, Green Machining, Cutting Forces*

1. INTRODUCTION

The literature indicates that most of the power used in metal machining is transformed into heat in the primary, secondary, and tertiary shear zones at the tool/chip interface. The heat increases elevate the temperature, which on the one hand, is favorable to the process by decreasing the workpiece shear strength and hardness, thus facilitating the cutting. On the other hand, it impairs tool life, dimensional tolerances, surface integrity (roughness, residual stresses), decreases productivity, increases costs (Klocke, 2011; Machado *et al.*, 2011; Trent & Wright, 2000).

One way to avoid the adverse effects of high temperature is to use lube cooling techniques. The industry-standard technique is the Cutting Fluid in Abundance - CFA. Byers (2016) explains that the CFAs act on the entire machine-tool-part assembly and contributes to the overall system cooling, decreasing the average temperature, especially the cutting tool, maintaining its mechanical integrity, especially hardness, in addition to lubricating the tool/chip interface, slip zone, reducing the Coefficient of Friction - CoF. Less friction, less heat, lower temperature, and consequently, process improvement in general. Said *et al.* (2019) estimates that in 2016 alone, the global consumption of non-biodegradable mineral-based CFs was ~ 13,726 million tons, with an increasing forecast of increase (Said *et al.*, 2019). According to Benedicto *et al.* (2017), in 2022, lubricants' global demand can reach 43.9 million tons (Benedicto *et al.*, 2017)

However, because Cutting Fluids - CFs are a toxic intake, it strongly affects the sustainable triple bottom line: social, Ambient and Economic. The social aspect affects human health, causing allergic reactions or even cancer (Ozcelik *et al.*, 2011). Ambient issues cause environmental damage through contamination of soils, sewers, rivers, and water sources (Bartz, 2001; Soković & Mijanović, 2001). Finally, economically it increases the production costs. Inside the automotive industry, some studies indicate that CFAs alone accounts for 7 to 17% of the total machining cost (King *et al.*, 2001) and can reach around 30% in exceptional cases (Demirbas & Kobya, 2017). Because of that, researchers, governments, and related entities have sought ways to mitigate these environmental impacts with stricter laws along with the Research and Development – R&D of more ecologically friendly techniques (Debnath *et al.*, 2014; Sharma *et al.*, 2015).

Alternative lubrication cooling methods have been studied and successfully applied, among them are Minimum Quantity of Lubricants - MQL, Minimum Quantity of Cooled Lubricant - MQCL, High Pressure Cutting Fluid - HPCF, cryogenic fluids (liquid nitrogen and CO₂), solid lubricants, nanoparticles, texturizations, high pressure, cooled

compressed air, among others (Debnath *et al.*, 2014; Sartori *et al.*, 2018; Sen *et al.*, 2019; Sharma *et al.*, 2009; Singh *et al.*, 2016; Zhang *et al.*, 2012).

All these methods, in some way, include wear or irreversible consumption of inputs. For example, when applied, liquid nitrogen quickly vaporizes and is dispersed in the atmosphere. The same goes for CO₂. Therefore, environmental impacts, albeit minor compared to CFAs, may be relevant, considering large-scale applications, apart from the high associated costs (Hong & Broomer, 2000; Yildiz & Nalbant, 2008).

Therefore, the main objective of this work is to evaluate an ecologically friendly alternative of Internally Cooled Tools - ICT in the turning of Grey Cast Iron by Continuous Casting (FUCO). The proposed system uses the concept of the closed cooling cycle, that is, without any fluid dispersion into the atmosphere, cooling only the cutting tool, maintaining its mechanical properties, while taking advantage of the good side of the high temperature of the part that is to decrease hardness and shear resistance, facilitating cutting. This study is part of the work developed by Bazon (2020).

Other works carried out at the Federal University of Uberlândia (UFU) such as France (2021) carried out temperature measurement studies with this system in comparison to dry cutting in gray cast iron turning using the tool-work thermocouple and welded thermocouple techniques, where a reduction in machining temperatures of up to 21.52 % was observed. And Barbosa (2021), which used the ICT system in turning of hardened D6 steels, increased tool life by 35% and increased cutting force by comparison with dry machining.

2. MATERIALS & METHODS

2.1. Cooling System Design

The Internal Channels - ICs technique was adopted in this work, with ducts passing directly inside a cemented carbide tool. The cooling system is composed of two Heat Exchangers – HEs. The Primary Heat Exchanger - PHE is an adopted conventional refrigerator, Prosdocimo brand, model 04180CBC201, 146 W. The freezer consists of thermal insulation, compressor, condenser, expansion device, and evaporator, Fig. 1.

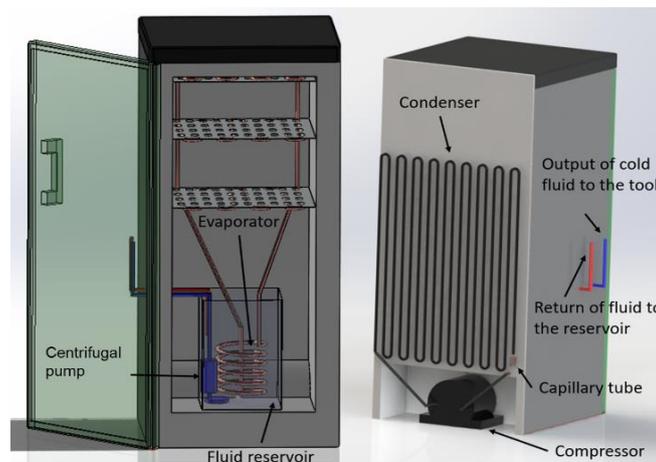


Figure 1. Primary Heat Exchanger – PHE Components

The Secondary Heat Exchanger – SHE is composed of a reservoir, a centrifugal pump, cold and hot ducts, and the adapted cemented carbide tool. The critical point is the reservoir responsible for storing the cooling fluid and changing heat with the PHE. A centrifugal pump (up to 22 Kpa) is responsible for circulating the coolant into the Internally Cooled Tool – ICT.

The ICT consists of an adapted cemented carbide tool, tool-holder, clamp, and shim with ducts for the coolant's passage. It was adapted a DSSNL2525X12-P tool holder model, Walter Tools brand, Fig. 2.

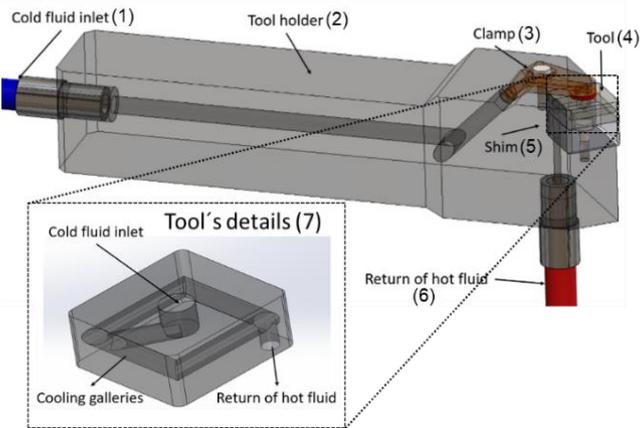


Figure 2. Internally Cooled Tools – ICT design in detail showing cooling channels.

The coolant gets into the system by the cold fluid inlet (1), passes through a specially adapted duct in the tool holder (2) until it reaches the clamp (3) and after the tool (4), where it will remove heat from the machining process and finally to the shim (5) and the hot outlet duct (6).

Figure 2 (7) shows details of the internal channels made by Electrical Discharge Machine - EDM in an ISO SNUN120412 carbide cutting tool K class. The coolant enters by the tool's top and returns by its bottom, passing through the channels (dark region, Fig. 2 (7)). This tool's design allows four edges to be cooled and useful. Table 2 contains the details of both PHE and SHE.

Table 1 Primary and Secondary Heat Exchangers specifications

PRIMARY HEAT EXCHANGER (PHE)	
Commercial Freezer (Brand/model)	Prosdócimo/04180CBC 201
Cooling Power [W]	146
Coolant	R 134
Voltage. [V]	220
Coolant pressure R 134 [KPa]	52
SECONDARY HEAT EXCHANGER (SHE)	
Coolant	Mono Ethylene Glycol (50%) water (50%)
Minimum Temperature [°C]	-25 °C
Pump	
Flow rate [l/min]	1.02
Voltage [V]	12
Coolant pressure [KPa]	22

2.2. Cast Gray Iron (FUCO) preparation

It was used a machining Pearlitic/Ferritic continuously Cast Gray Iron - GCI, ASTM 48 – class 30. According to the manufacturer (TUPY, 2020), this material contains lamellar graphite, form VII, A-type, 3 to 6 size (ASTM A 247). The matrix is predominantly pearlitic, with 5 to 20% ferrite in the center, Fig. 3 (b). The border contains graphite D-type, 6 to 8 size, predominantly ferritic, with ~5 % dispersed carbides, Fig. 3 (a). Table 3 includes the typical material chemical composition and mechanical properties.

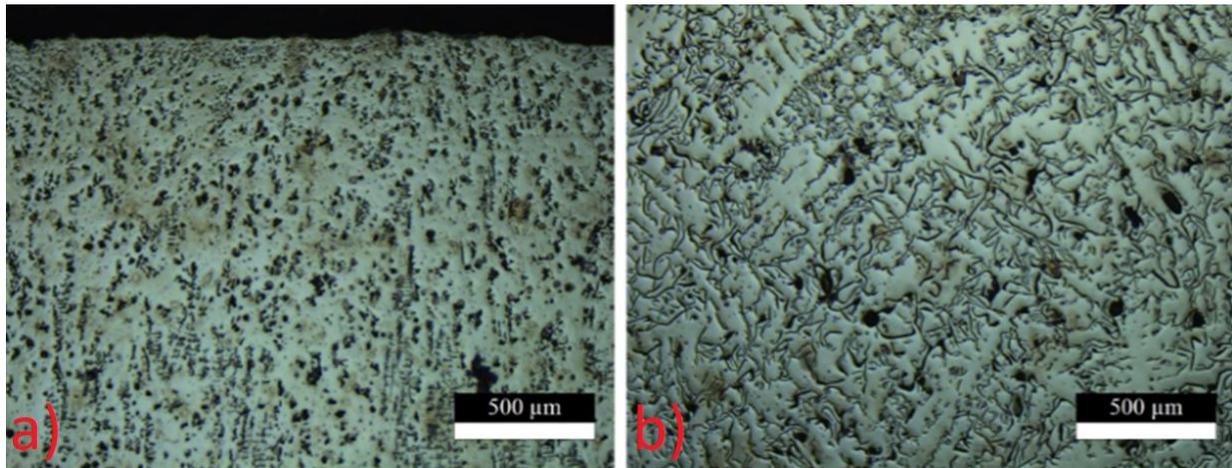


Figure 3. ASTM 48 (Class 30) Cast Gray Iron Microstructure in border (a) and the centre (b)

Table 2 ASTM 48 (Class 30) Cast Gray Iron (TUPY, 2020)

Element	%
C	2.8 ~ 3.70
Si	2.20 ~ 2.70
Mn	0.20 ~ 0.70
S	0.20 max
P	0.15 max
Cr	0.10 max
Mechanical properties	
Tensile Strength	150 MPa
Hardness	180 HV

2.3. Measuring procedures

For the measure of the cutting forces: was used a dynamometer coupled to the tool holder, Model 9265B, and a Model 5070 A signal amplifier, both manufactured by Kistler, Fig. 4. A data acquisition board from National Instrument USB, 6251DaqPad model, was used to manage the data acquisition system with LabVIEW® software. The cutting force component was measured, with a time of 10 s and an acquisition rate of 100 hz. The data were processed in MATLAB software.

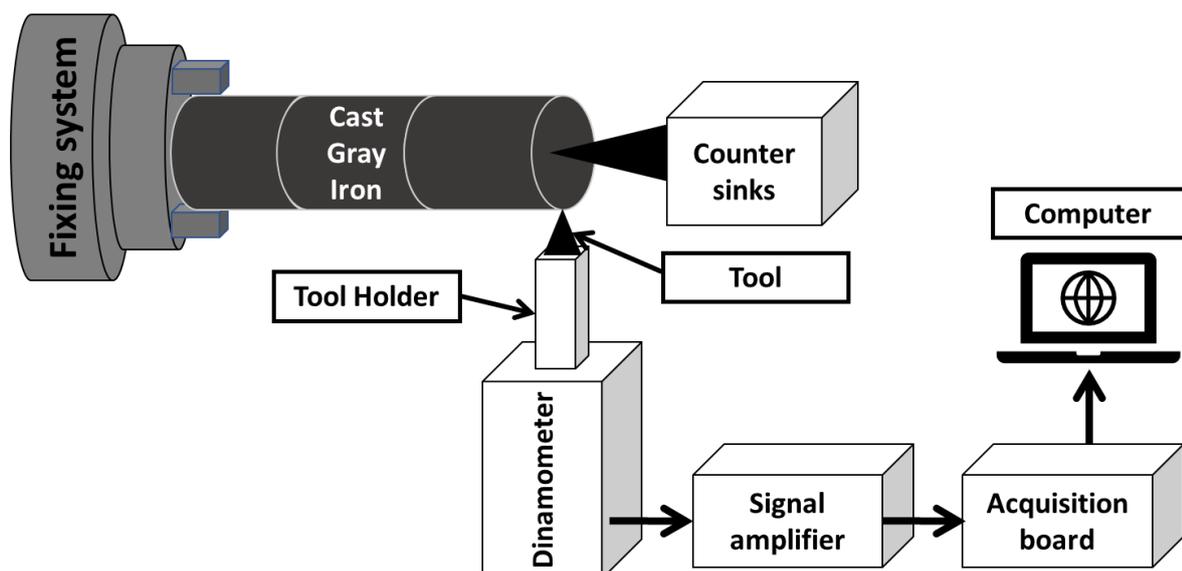


Figure 4. Acquisition system scheme using the dynamometer Kistler.

2.4. Machining procedures

It was proposed a univariate input variable, cutting speed, and it was performed for both Cutting Fluids in Abundance – CFA, and ICT. The cutting speed were: 40, 60, 80, 100, 120, 160, 200, 240, 360, 480 and 600 m/min. The depth of cut (a_p) and feed (f) were kept constant at 1.0 mm and 0.1 mm/rot, respectively. Table 4 contains the summary of experimental conditions

Table 3 Summarize of experimental conditions

Machine Tool	ROMI CNC lathe Multiplic 35 D machine
Workpiece material	FUCO® FC 200 Grey Cast Iron
Size	Ø 91.2 X 237 mm
Hardness	91 HRB
Process parameters	
Cutting speed	40, 60, 80, 100, 120, 160, 200, 240, 360, 480 and 600 m/min
Feed rate	0.1 mm/rev
Depth of cut	1 mm
Ambient	ICT or CFA
Cutting tool (inserts)	ISO SNUN120408 adapted
Oil	ECOCOOL P 1977 BF (10%)
Coolant Tool	50% mono ethylene glycol and 50% water

CNC: computer numerical control ICT: Internally Cooled Tool
CFA - Cutting Fluid in Abundance

3. RESULTS & DISCUSSIONS

3.1. Forces analysis

The cutting forces as a function of cutting speed and ambient are shown in Fig. 5.

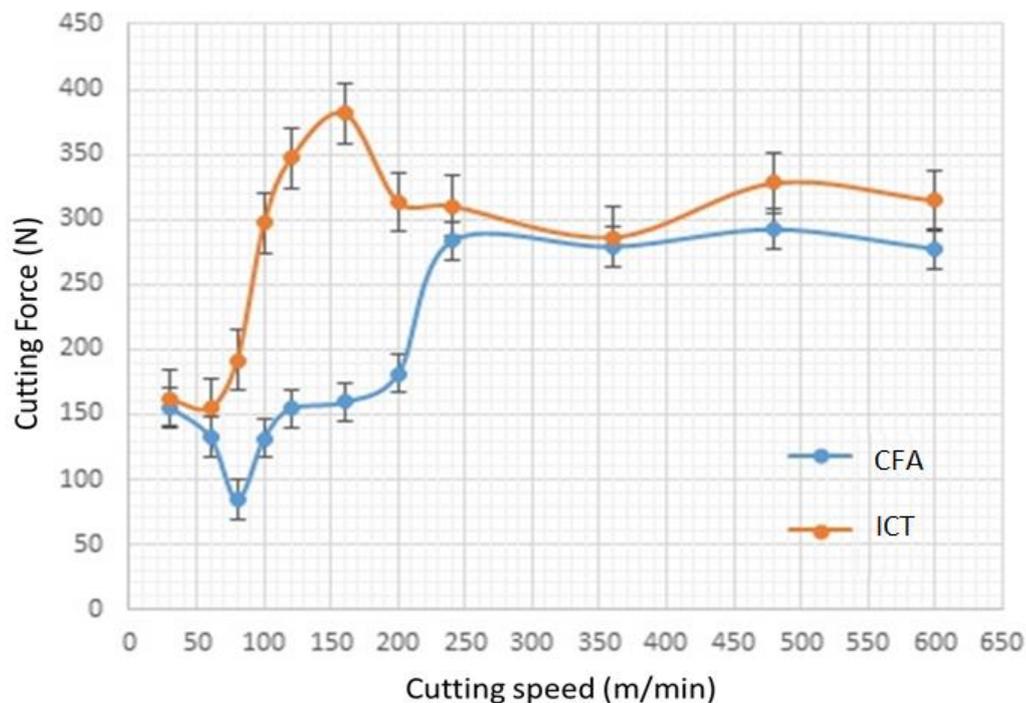


Figure 5. Univariate cutting forces in the function of cutting speed

The extensive literature indicates that higher cutting speeds generate a higher material removal rate with higher friction, heat generation, and temperature increase. The increase in temperature contributes to reduce the mechanical

properties of the material, particularly shear strength and hardness, and thus contributes to the reduction of cutting forces (Klocke, 2011; Machado *et al.*, 2011; Trent & Wright, 2000). Contrary to the literature, the cutting force increased along with the cutting speed. It fact can be explained by the formation of segmented chips and lamellar structure, typical of gray cast iron, which increases the contact chip/tool length and, consequently, the cutting forces.

Analyzing the CFA and ICT comparison, there are two hypotheses for the cutting forces to be higher in the case of ICT. The first is related to the lubricity effect of the prominent CFA medium for low cutting speeds (up to ~150 m/min), which contributes to reducing the Coefficient of Friction (CoF) and facilitating chip removal on the tool rake face.

The second hypothesis refers to the effect of the sharp cooling of ICT. The fluid now has little or almost no access to the cutting zone for high cutting speeds, acting more as the system's cooling. In this case, lower forces indicate more elevated temperatures, because as discussed, the high temperatures perform facilitating cutting. Therefore, it is reasonable to infer that the ICT system efficiently removes heat from the tool. To confirm this, temperature tests should be carried out.

For the CFA, the lowest force occurred close to 80 m/min, possibly due to Build-up Edge - BuE, and increased up to 240 m/min, where it stabilized. In the case of ICT, the forces increase considerably from 60 to ~160 m/min, where it drops considerably until it stabilizes from 200 m/min. Possibly there is the formation of BuE for the ICT ambient too, especially due to the inextricable lack of lubricity that facilitates the mechanisms of adhesion.

4. CONCLUSIONS

This study verified the applicability of Internally Cooled Tools - ICT compared to the conventional method of Cutting Fluid in Abundant - CFA. It was proposed a univariate input variable, cutting speed, performed for both Cutting Fluids in Abundance – CFA, and ICT. The cutting speed were: 40, 60, 80,100, 120, 160, 200, 240, 360, 480 and 600 m/min. The depth of cut (a_p) and feed (f) were kept constant at 1.0 mm and 0.1 mm/rot, respectively. The main conclusions indicate that:

- *Contrary to the literature, the cutting force increased along with the cutting speed. It can be explained by the formation of segmented chips and lamellar structure, typical of Gray Cast Iron, which increases the chip/tool contact length and the cutting forces. Another explanation is the possible presence of a build-up edge.*
- *Cutting forces were higher for all ICT conditions, and two hypotheses were formulated to explain this. The first is related to the lubricity effect of the prominent CFA medium for low cutting speeds (up to ~150 m/min), which contributes to reducing the Coefficient of Friction (CoF) and facilitating chip removal on the tool rake face.*
- *The second hypothesis refers to the exceptional cooling of the ICT. The cutting fluid now has little or almost no access to the cutting zone for high cutting speeds, acting more as the system's cooling. In this case, lower forces indicate more elevated temperatures, because as discussed, the high temperatures perform facilitating cutting. Therefore, it is reasonable to infer that the ICT system efficiently removes heat from the tool. To confirm this, temperature tests should be carried out.*
- *Finally, the ICT system is a promising eco-friendly technique, even cooling just the tool and keeping the benefits of high temperatures and material softening. Further studies and more development are necessary, especially about the lack of lubricating effect, which could be surprised by other techniques, such as solid lubricants, coatings, textured tools, MQL, etc.*

5. ACKNOWLEDGEMENTS

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