

INSTITUTO TECNOLÓGICO DE AERONÁUTICA



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**COMPUTATIONAL METHOD FOR
TEMPERATURES AND HEAT FLOWS
ANALYSIS OF ORTHOGONAL CUTTING 1045
STEEL BY THERMAL IMAGING**

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COMPUTATIONAL METHOD FOR TEMPERATURES AND HEAT FLOWS ANALYSIS OF ORTHOGONAL CUTTING 1045 STEEL BY THERMAL IMAGING

This publication was accepted like Final Work of Undergraduation Study

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I dedicate this work to my family, which have always supported me in my decisions and are the most happy ones with this academic achievement.

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"The man that makes no mistakes does not usually do anything."
— BISHOP W.C.MAGEE

Resumo

Métodos de inspeção e monitoramento têm sido utilizados cada vez mais para garantir a qualidade de processos. No campo da usinagem existem muitos parâmetros importantes para assegurar que o processo forneça os resultados estimados. O acabamento superficial de uma peça usinada e a vida útil de uma ferramenta, por exemplo, sofrem influência direta da energia térmica gerada nas zonas de calor. Devido a isso, existem muitos métodos teóricos para a modelagem de temperatura distribuída pela zona de corte, mas ainda faltam ferramentas que possam permitir a validação prática de tais métodos. Embora ainda existam desafios no uso adequado da termografia, essa tecnologia faz possível o desenvolvimento de métodos computacionais que permitam o processamento de imagens térmicas e, conseqüentemente a posterior análise de fluxos de calor e partições dessa energia. Este trabalho apresenta um método computacional desenvolvido em MATLAB, com o suporte da toolbox de processamento de imagens, para análise de imagens térmicas, fornecendo resultados de campos de temperatura, energias internas, fluxos de calor e outras variáveis de interesse que possam ser utilizadas no monitoramento da usinagem e no estudos de melhores parâmetros de corte.

Abstract

Methods for inspection and monitoring have been used each time more to guarantee the quality of processes. In the machining field there are many important parameters to assure that a process provide the designed results. The superficial finishing of a workpiece and the life of tool are some examples subjected to the direct influence of thermal energy generated in the cutting zones. Due to it, there are a lot of theoretical methods for temperature modeling along the cutting zone, but still there is a lack of tools able to allow a practical validation of these methods. Although many challenges still prevail on the suitable use of thermography, this technology makes possible the development of computational methods that allows the thermal image processing and, consequently, the heat flow and heat partition analysis afterwards. This paper comes to present a computational method developed on MATLAB, with image processing toolbox support. It makes thermal image analysis, providing results about temperature fields, inner energies, heat flows and other variables of interest that can be used on machining monitoring and studies to improve cutting parameters.

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List of Abbreviations and Acronyms

MATLAB	Numerical computation software from MathWorks
GUI	graphic user interface
GUIDE	graphic user interface development environment
AISI	American iron and steel institute
WZL	Werkzeugmaschinenlabor (Laboratory of Machine Tools)
FOV	Field of view
fps	Frames per second

List of Symbols

F_c	Cutting force on the power direction [N]
F_p	Passive force [N]
v_c	Cutting velocity [m/min]
v_{chip}	Exit velocity of chip [m/min]
P	Total power developed along cutting process [W]
w	Width of tool [mm]
a_p	Depth of cut [μm]
t_c	Chip thickness [μm]
T_e	Environment temperature [$^{\circ}C$]
k	Heat conductivity of tool material [W/mK]
c_p^T	Heat capacity of tool [J/cm^3K]
c_p^W	Heat capacity of workpiece [J/kgK]
α	Rake angle [$^{\circ}$]
γ	Clearance angle [$^{\circ}$]
ϕ	Shear angle [$^{\circ}$]
r_{β}	Cutting edge radius [μm]
ϵ	Emissivity
L	Length of chosen isotherm [pixel]
$\frac{dT}{dz}$	Variation of temperature along normal of chosen isotherm [$^{\circ}C/pixel$]
\dot{Q}_T	Heat flow through tool [W]
\dot{Q}_C^{out}	Energy carried away by chip [W]
\dot{Q}_C^{in}	Energy carried in by chip [W]
\dot{Q}_W	Heat flow through workpiece [W]
\dot{Q}_{inside}	Total energy into the control volume [W]
$\dot{Q}_{outside}$	Total energy out to the control volume [W]
\dot{Q}_{shear}	Total energy generated in the primary shear zone [W]
T_C^{out}	Temperature of chip along line of end of contact [$^{\circ}C$]
p_T	Partition of heat that goes to tool
p_C	Partition of heat that goes to chip
p_W	Partition of heat that goes to workpiece

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1 Introduction

In many machining cases, orthogonal cutting may be considered a good approximation to perform on the major cutting edge, that is why it has been extensively studied (SHAW; COOKSON, 2005). For instance, planing and facing processes are some examples that orthogonal cutting conditions can be observed.

Also, it is known that thermal behavior during the cutting process, as temperature fields and heat flows, has an important influence on tool life, surface finish and metallurgical structure of workpiece and machinability. Then, the study of thermal analysis on orthogonal cutting case shall be able to provide a better comprehension of many studies concerning thermal modeling of metal cutting processes (KOMANDURI; HOU, 2000), (KOMANDURI; HOU, 2001).

1.1 Overview of metal cutting

There are different ways to change raw material, as additive and subtractive (SHAW; COOKSON, 2005). The additive processes occur when separated materials are put together, like 3D printing. On the other hand, subtractive way removes unnecessary material, which happens for machining processes as turning, milling and, in this paper, orthogonal cutting. The cutting process is composed basically by chip, tool and workpiece (figure 1.1). Many parameters are responsible for the surface finishing of the workpiece, for example. Depth of cut, cutting velocity, cutting material are some of these parameters. It is fundamental to use the right parameters for each type of cutting process, otherwise it can harm the final result and the process itself.

1.2 Heat zones

In machining there are 3 main regions of interest from where comes the heat produced during the cutting process (SHAW; COOKSON, 2005). The first area represented on figure 1.1 is called primary shear zone and is located along the shear plane, which is the edge

between the undeformed workpiece and the chip. The second area is the plane of contact between tool and chip, also known as secondary shear zone or friction zone. As for third area, it is related to the wear caused due the friction between tool and finished workpiece surface, due to it is called wear zone.

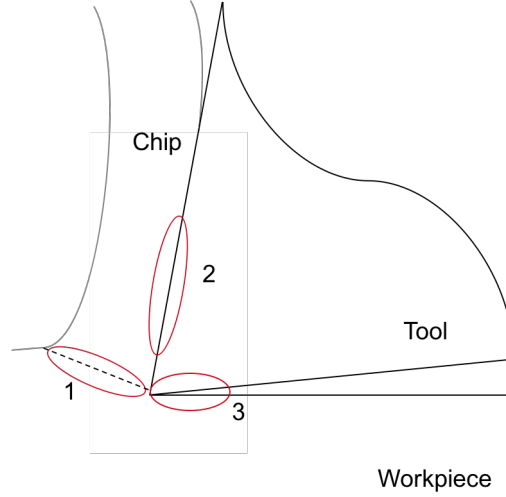


FIGURE 1.1 – Regions of interest

1.3 Mechanics of orthogonal cutting

In this paper it will be show numerous correlations among forces, stresses and dimensions for example. For this purpose it is important to discuss geometrical correlations in the composite cutting force circle (figure 1.2).

From the figure 1.2 it can be stated about forces on the primary shear zone reference F_S and N_S :

$$F_S = F_P \cos \phi - F_Q \sin \phi \quad (1.1)$$

$$N_S = F_Q \cos \phi + F_P \sin \phi \quad (1.2)$$

Also, for the forces on the chip flow reference:

$$F_C = F_P \sin \alpha + F_Q \cos \alpha \quad (1.3)$$

$$N_C = F_P \cos \alpha - F_Q \sin \alpha \quad (1.4)$$

These equations provide all auxiliary forces related to the known passive force F_Q and

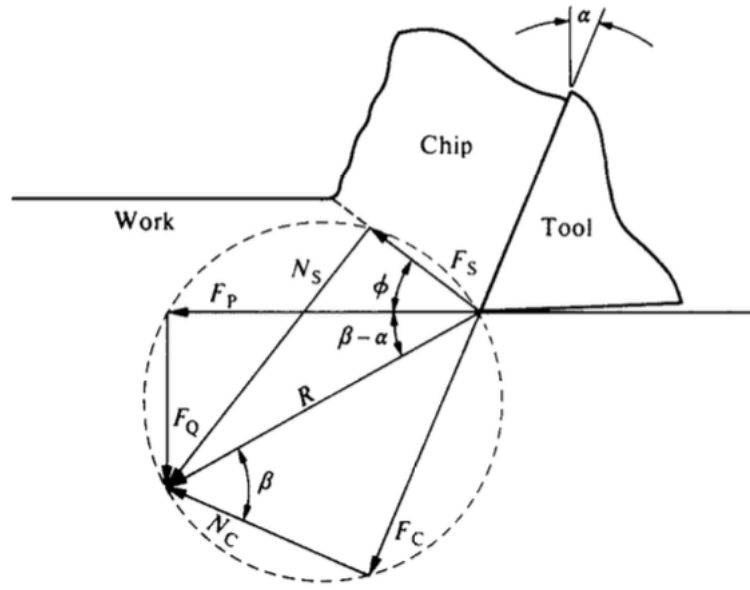


FIGURE 1.2 – Cutting forces (SHAW; COOKSON, 2005)

force on the cutting direction F_P . Now, the variables of interest can be easily calculated, as the friction coefficient:

$$\mu = \frac{F_C}{N_C} = \frac{F_Q + F_P \tan \alpha}{F_P - F_Q \tan \alpha} \quad (1.5)$$

Now the equations concerning about stresses are:

$$A_S = \frac{wa_p}{\sin \phi} \quad (1.6)$$

$$\tau = \frac{F_S}{A_S} = \frac{(F_P \cos \phi - F_Q \sin \phi) \sin \phi}{wa_p} \quad (1.7)$$

$$\sigma = \frac{N_S}{A_S} = \frac{(F_P \sin \phi + F_Q \cos \phi) \sin \phi}{wa_p} \quad (1.8)$$

Where A_S is the area of the shear plane, τ is the shear stress and σ is the normal stress.

Another important parameter is the cutting ratio r , which can provide an important relation between the main cutting velocity and the chip outlet velocity. It is found experimentally that there is no change in density of metal during the cutting process and also

for $w/a_p \geq 5$ the width of the chip is the same of the workpiece. Then, the equations are:

$$a_p w l = a_{pc} w_c l_c \quad (1.9)$$

Where a_p , w and l are the depth of cut, width of cut and length of cut respectively. Then, the cutting ratio is defined by:

$$r = \frac{a_p}{a_{pc}} = \frac{l_c}{l} \quad (1.10)$$

Having the cutting ratio, it is now possible to correlate cutting velocity v and chip outlet velocity v_c by means of the following equation:

$$v_c = r v \quad (1.11)$$

1.4 Objective

The aim of this paper is to develop a computational method to analyze thermal images generated during the orthogonal cutting of AISI 1045 metal, focusing on the transient state due to the short time of cutting. It will be analyzed temperature distribution along the cutting tool, heat flows through tool, chip and workpiece.

1.5 Structure

This work is divided into 6 Chapters, including this **Introduction**, plus one Appendix.

The second chapter, **State of the Art**, describes the existing technology which is relevant for the scope of this paper and upon which the work was built.

The third chapter, **Materials and Methods**, describes the methodology and materials that conducted the experiments.

The fourth, **Code Implementation**, describes the logical implementation of the final analysis code.

The fifth, **Results**, presents the results and discussions about the outputs of the final code.

The sixth and final chapter, **Conclusion**, sums up what was accomplished in this work and suggests how it may be expanded for new processes.

The Appendix **Source Code** contains all the code written for the program.

2 State of the Art

2.1 Infrared Thermography

Infrared thermography is a contactless way to measure infrared electromagnetic energy. It makes possible to observe contours of different bodies due to their temperature distribution, since every body is able to emit electromagnetic radiation when its temperature is above absolute zero. For this reason, it is a very important technology in military use, because it allows objects be seen even without proper illumination or in total lack of light situations.

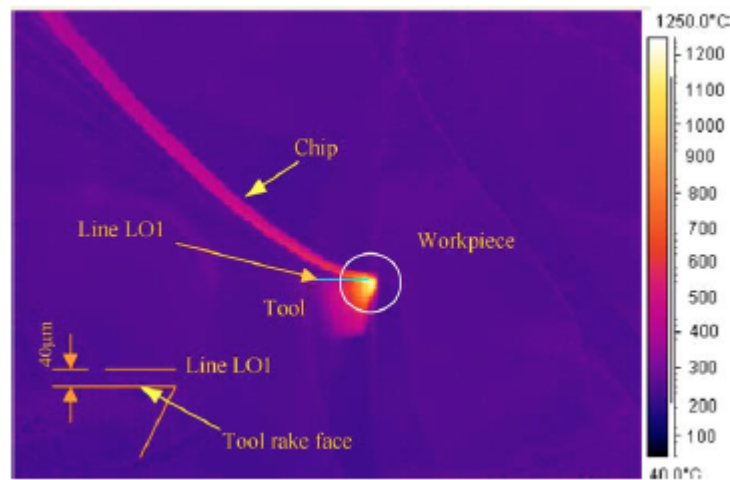


FIGURE 2.1 – Infrared photography of a cutting process (ABUKHSHIM *et al.*, 2006)

The thermography tool is able to work in two different ways: passive and active. The passive way occurs when the subject matter has its temperature different from the environment (often higher). On the other hand, the active way needs an external heat source to induce a reasonable contrast between the object and the background (MALDAGUE, 2000). For the case under study, high speed thermography has its positive and negative points. On the positive side, it may be mentioned:

- Fast inspection rate (reasonable number of images of high speed cutting)

- Contactless (no interference during the cutting process)
- Easy interpretation of the results (indexed image with temperatures in each pixel)

But it is also important to mention the difficulties that in this method still prevail:

- Only a limited thickness can be measured (under the main surface)
- Determine a suitable emissivity is a challenge (it changes with temperature variation)

2.2 Image Processing

Systems of vision have been very often approached with the current fast technology development and intelligent systems. They are used for the most diverse segments, as military and medical areas. Image processing has quickly gaining highlight. For instance, this is essential when comes to finding a pattern or extract an specific feature in a image.

Colorful or gray scaled images can be treated as matrices with dimensions given by their pixel resolution. Each pixel corresponds to a cell inside this matrix and each cell contains a relevant information, it could be a level in grayscale, a coordinate or a temperature as in the case of this paper. Since they are matrices, they can be easily manipulated by means of mathematical operations and, consequently, processed to highlight one specific property or more.

Many studies have been and are being done about the use of image processing on machining. It was used to monitor flank wear of cutting tools (JEON; KIM, 1988), (KURADA; BRADLEY, 1997) and also for detection of chatter during cutting processes. There are uncountable ways which this tool can be applied to improve processes and quality of final products in machining industry. The fast development of computer hardware makes the processing time of these images continuously shorter, allowing system of vision be incorporated in online monitoring and, then, providing a real time feedback.

3 Materials and Methods

3.1 Experimental Setup and Materials

The experiments were carried out on WZL shop floor, located in Aachen in Germany, acquiring thermal images by means of high speed infrared camera FLIR SC7600 (with frame rate of 328 fps and a resolution of 640 x 512 pixels), it was equipped with a macro lens 1:1 and FOV 9.6 x 7.7 mm. The test bench works in a way that the tool stays in a fixed position in relation to the camera, keeping the relative distance between tool and camera constant, then the scale factor provided by this setting was 15 $\mu\text{m}/\text{pixel}$. It allows the metric conversion for future post processing of images.

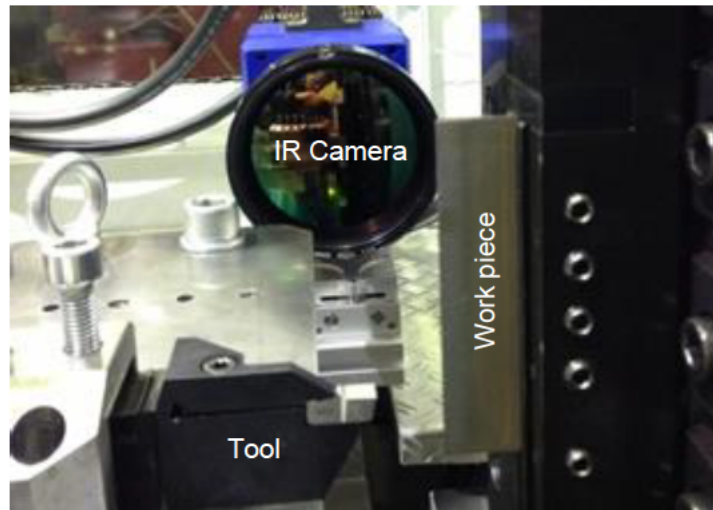


FIGURE 3.1 – Experimental setup (AUGSPURGER *et al.*, 2016)

An important factor for a reliable temperature measurement is the correct choice of the components' emissivity. To make it easier, the tool was coated with a black ink, allowing the emissivity valuation for this case, which provided a value of $\epsilon = 0.85$. It is also important to highlight the camera settings, factors as integration time and filters are essential to determine a reliable measurements due to the amount of electromagnetic radiation received on camera's sensors. The higher are the temperatures higher is the energy produced, then smaller should be the integration time, which is the time that sensor of

energy receives radiation and converts into temperature afterwards. These configurations allowed measurements in a range from 200 °C until 900 °C.

The tool material was uncoated carbide insert (Sandvik H13A), with rake angle 6°, clearance angle 3°, cutting radius $r_\beta < 5\mu\text{m}$ and width 4.4 mm. The workpiece material was AISI 1045 normalized and its dimensions were 3.5 x 200 x 80 mm (width, length, height respectively). For the given range of temperature, the thermal conductivity was estimated in $k = 75.4\text{W/mK}$ and for tool heat capacity was built a regression function ($c(T)$) for corresponding temperature and heat capacity (equations 3.1 and 3.2).

For force acquisition during the process, it was used a three-component piezoelectric force platform, determining the cutting force and passive force. Since the cutting process is carried out in a linear and constant motion, it is possible to determine the overall power P with velocity and cutting force. From the values obtained of forces along the cutting process it was taken a mean value to be used on power calculation afterwards, equation 3.3.

All the experiments were held without coolant, with cutting velocities of 100 m/min and 150 m/min and $a_p = [0.2, 0.3, 0.4, 0.5]$ mm (table 3.1). The analysis method was built on MATLAB platform with the support of its image processing toolbox. This was the chosen software due the easy connection between FLIR software and MATLAB, since FLIR software can export its images to .mat format, which are indexed matrices projected to MATLAB environment. Each pixel from the exported images contains information about position and its temperature.

Experiments	Cutting Velocity [m/min]	Uncut chip thickness [μm]	Integration time [μs]	Cutting Force [N]	Passive Force [N]	Heat treatment
VP41_1_H200_V100_C45_MF_425	100	200	425	1500	1000	Normalized
VP41_2_H200_V100_C45_MF_425	100	200	425	1565	1005	Normalized
VP42_1_H300_V100_C45_MF_425	100	300	425	2250	1159	Normalized
VP42_2_H300_V100_C45_MF_285	100	300	285	2136	1079	Normalized
VP43_1_H400_V100_C45_MF_285	100	400	285	2716	1118	Normalized
VP45_2_H200_V150_C45_MF_425	150	200	425	1448	688	Normalized
VP46_1_H300_V150_C45_MF_285	150	300	285	2006	801	Normalized
VP46_2_H300_V150_C45_MF_285	150	300	285	2004	875	Normalized
VP49_1_H400_V150_C45_MF_285	150	400	285	2675	1046	Normalized
VP49_2_H400_V150_C45_MF_285	150	400	285	2590	1000	Normalized
VP50_1_H500_V150_C45_MF_285	150	500	285	3220	1120	Normalized
VP50_2_H500_V150_C45_MF_285	150	500	285	3178	1162	Normalized

TABLE 3.1 – Design of experiments (AUGSPURGER *et al.*, 2016)

As a machining process, the orthogonal cutting performance is subjected to many

parameter like material of workpiece, shape of tool, depth of cut and others. Because of it, the developed algorithm needs the information about all these parameters to work as close as possible of real conditions. Then, all the input data necessary to the can be summarize on the following table

Inputs					
Tool		Camera		Workpiece	
Heat Conductivity [W/(mK)]	75,4	Pixel pitch (Infrared Camera) [mm/pixel]	0,015	Length of the workpiece [mm]	200
Heat Capacity [J/(cm ³ K)]	Interpolation*	Maximum digit level valid (FLIR X)	8192	Heat Capacity [J/(kgK)]	Interpolation**
Rake Angle [°]	6	Maximum digit level valid (FLIR SC7600)	16000	Workpiece Material	AISI 1045 (normalized)
Clearance Angle [°]	3	Frame Rate (Infrared Camera) [Hz]	328	Width [mm]	3,5
Cutting edge radius [μm]	< 5	Minimum valid temperature for the frames [°C]	200	Percentage of the deformation energy converted into heat	0,9
		Emissivity (Experimentally determined - tool and workpiece coated)	0,85	Density (based on steel) [kg/m ³]	7874

TABLE 3.2 – Algorithm inputs (AUGSPURGER *et al.*, 2016)

The heat capacities of tool and workpiece material are used as an interpolation function on the code, using da data provided on tables 3.3 and 3.4. The functions are given by the following equations:

$$c_p^T = 2.51 \times 10^{-10} \times T^3 - 1.99 \times 10^{-6} \times T^2 + 0.0027 \times T + 3.09 \quad (3.1)$$

$$c_p^W = -4.39 \times 10^{-7} \times T^3 - 7.07 \times 10^{-4} \times T^2 + 0.0489 \times T + 481.21 \quad (3.2)$$

Workpiece Material			
Temperature [°C]	Heat Capacity [J/(kgK)]	Heat Conductivity [W/(mK)]	Density [Kg/m ³]
20	474,62	48,03	7820,9
100	487,94	47,21	7794,3
200	501,2	45,82	7764,2
300	521,29	42,74	7732
400	545,69	39,1	7697,4
500	572,7	35,35	7660,4
600	601,83	31,73	7620,9
700	632,89	28,33	7578,7
800	696,29	23,52	7579,4
900	693,79	25,25	7528,3
1000	691,3	26,61	7475
1100	688,81	27,9	7419,7
1200	686,34	29,34	7362,3

TABLE 3.3 – Workpiece material data (AUGSPURGER *et al.*, 2016)

Tool Material		
Temperature [°C]	Heat Capacity [J/(cm³K)]	Heat Conductivity [W/(mK)]
20	3,2	100
100	3,24	94,8
200	3,59	88,3
300	3,79	81,9
400	3,9	75,4
500	3,97	68,9
600	4,05	66,7
700	4,14	64,8

TABLE 3.4 – Tool material data (AUGSPURGER *et al.*, 2016)

3.2 Methods

3.2.1 Power calculation

This is a known simple method that is stated on the following equation 3.3

$$P = F_c v_c \quad (3.3)$$

3.2.2 Thermal enegy - chip and tool

The methods used in this paper to calculate heat flow through the tool and the energy carried away by chip are based on (BOOTHROYD, 1963).

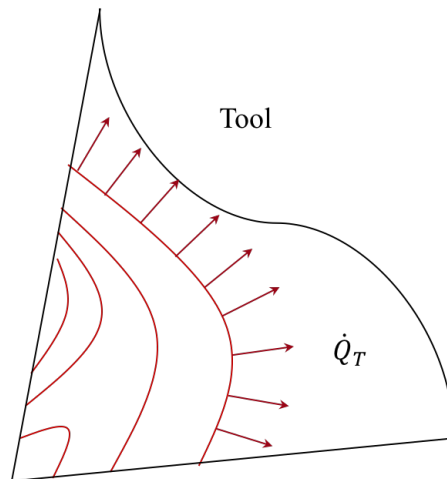


FIGURE 3.2 – Heat flow through tool

Besides the temperature matrix, it is necessary to calculate heat flow through tool the heat conductivity, the length of the chosen isothermal line, the temperature gradient

normal to this isotherm and the width of the tool. The calculation is given by the following equation:

$$\dot{Q}_T = kL \frac{dT}{dz} w \quad (3.4)$$

For the energy carried away by the chip when it is flowing through control volume, the variables necessary to calculate this value are the heat capacity function $c_p(T)$, the chip temperature distribution along the line where the chip loses contact with tool T_C^{out} , the environment temperature T_e , the velocity of chip normal to the line of end of contact v_{chip} , the chip thickness t_C and the chip width w .

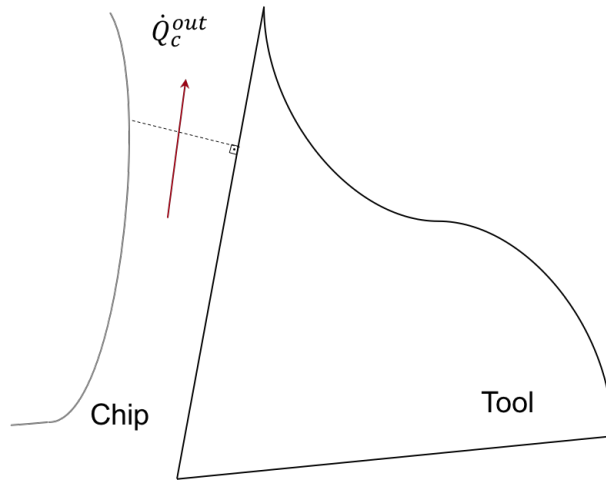


FIGURE 3.3 – Thermal energy carried away by chip

The equation for this energy is represented below:

$$\dot{Q}_C^{out} = c_p^W (T_C^{out} - T_e) v_{chip} t_C w \quad (3.5)$$

That way, having the location and the temperature of each pixel related to the isotherms and the line of end of contact chip - tool, the math necessary to perform these equations is simple, providing reliable outcomes.

3.2.3 Volume control

For matter of validation of the presented method and the lack of measurable temperatures on the workpiece surface, it was designed the control volume on figure 3.4.

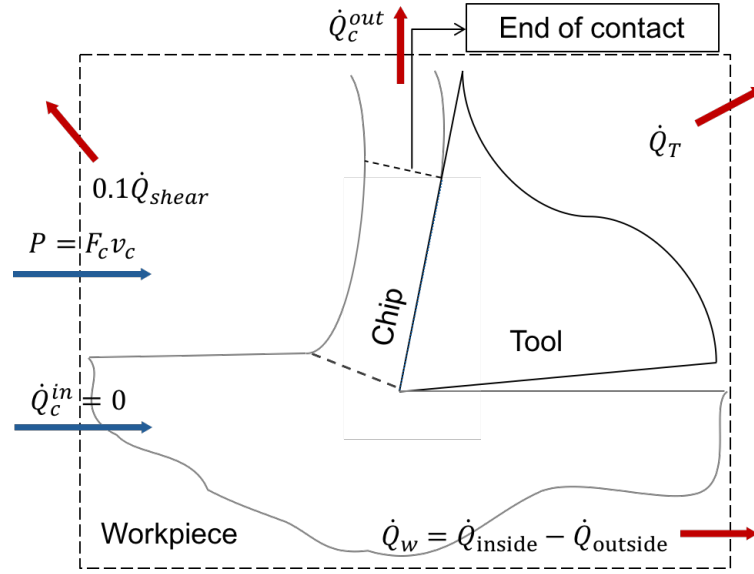


FIGURE 3.4 – Control volume

The shear energy used to raise the temperature of the heat zones is calculated by means of equation 3.6

$$\dot{Q}_{shear} = F_c v_c - F_p v_{chip} \quad (3.6)$$

It is estimated that 90% of this energy generated in the primary shear zone (\dot{Q}_{shear}) is converted into sensible heat (TRIGGER, 1942), then the others 10% are soon dissipated out the control volume. Then, the energy balance of the control volume will provide:

$$\dot{Q}_W = P - \dot{Q}_T - \dot{Q}_C^{out} - 0.1\dot{Q}_{shear} \quad (3.7)$$

4 Code Implementation

4.1 MATLAB environment

As mentioned on chapter 3, FLIR software provides as output variables indexed matrices in .mat format, which is MATLAB variable format. Each pixel contains temperature information about itself, it is possible to visualize an example on a scaled image on the following figure:

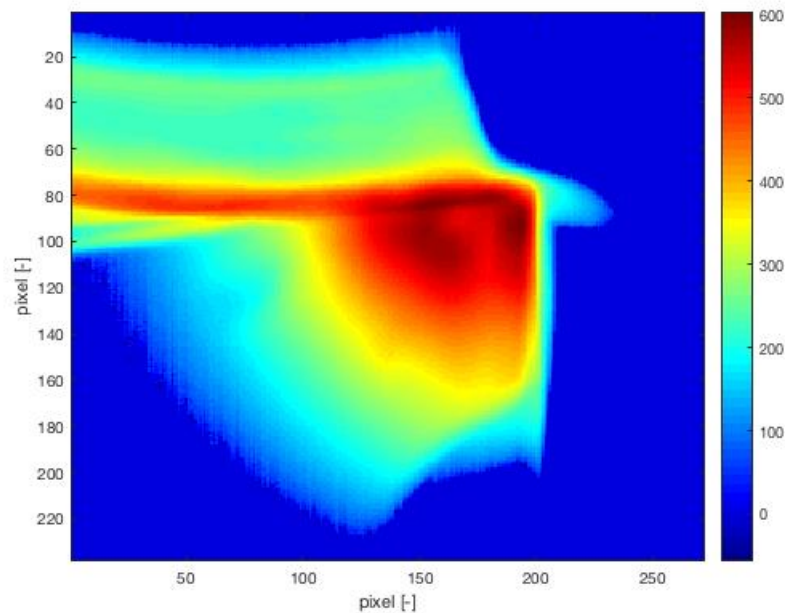


FIGURE 4.1 – Scaled image showing temperature distribution

From figure 4.1 with MATLAB Image Processing Toolbox support it possible to extract much information about the image, such as:

- Edges recognition
- Image segmentation for tool, chip and workpiece
- Detection of tool tip

- Determine isotherms along tool

4.2 Auxiliar functions

4.2.1 Contour plot

This is an important tool for this paper, contour plot is able to provide the same level curves. Since the variable used on the process is a temperature matrix, this tool will calculate continuous lines, in which each pixel has a very close temperature measurements. Doing it with a determined and small tolerance, the lines calculated are isotherms of the image. Then, with these lines it is also possible to get its coordinates, which it will be essential to calculate heat carried away from volume control by means of tool.

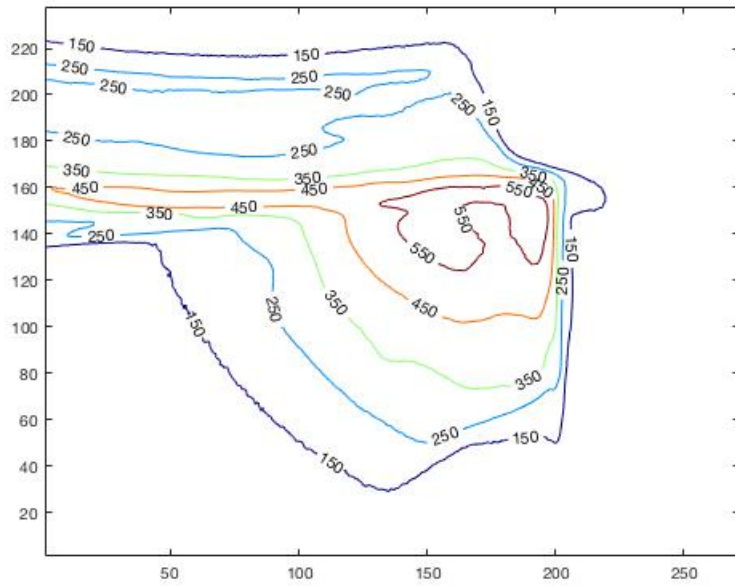


FIGURE 4.2 – Contour plot

4.2.2 Hough lines transformation

Hough transform is an extensive method used in computer vision. It is an extraction feature for complex geometries, using normal parameterization for straight lines (DUDA; HART, 1972). Concerning about the images, the rake and clearance face can be mapped by means of hough lines transformation in MATLAB. It is necessary to provide a probable angle range in what the angular coefficient of sought lines are defined. More precise is this angle range, more reliable and faster will be the output.

The test bench, where the experiments were held, allows a fixed placement of tool.

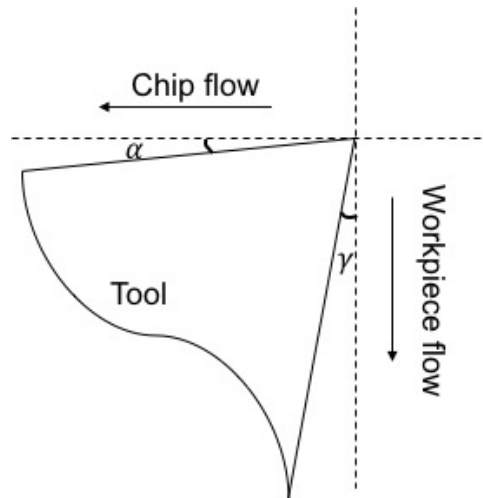


FIGURE 4.3 – Placement of tool

It means the angle between the rake face and horizontal line and the angle between clearance face and vertical line are always the designed rake and clearance angles, respectively. In other words, the tool does not rotate in relation to the reference axes. Because of this, it is possible to perform hough transformation on the image, being very accurate. As the rake and clearance angle are always 6° and 3° , respectively, the hough transform processing will last a shorter time with predetermined angles than otherwise.

4.3 Implementation steps

4.3.1 Overview

The final aim of the program was able to identify the tool and chip shapes, then the analysis could extract and provide features that were essential for the results of this paper. By means of image processing and some input data, features like maximum cutting zone temperature, maximum chip temperature, heat flows through chip and tool are some examples of what the code is able to provide.

4.3.2 Finding tool edges

As mentioned in the subsection Hough lines transformation, the method to find tool edges has to provide an accurate range of angles that the rake and clearance angles are inserted. The process is simple and it is demonstrated as follows:

```

1 function obj = calculateCoordinates(obj)
2     obj.BW = edge(obj.frame, 'sobel');

```

```

3      %-----Finding the clearance face-----
4      [H, THETA, RHO] = hough(obj.BW, 'Theta', 2:5); %Hough transformation
5      P = houghpeaks(H, 10);
6      obj.lines = houghlines(obj.BW, THETA, RHO, P, 'FillGap', 15, 'MinLength'
,10); %Here we can find the lines of cutting edge and afterwards find the
coordinate of the tool tip
7      l = length(obj.lines);
8      obj.coordCF = [];
9      for i=1:l
10         Theta = obj.lines(i).theta;
11         t1 = obj.lines(i).point1;
12         t2 = obj.lines(i).point2;
13         rho = obj.lines(i).rho;
14         if rho < 204 && rho > 198
15             obj.coordCF = [t1;t2];
16             obj.ClearanceAngle = Theta;
17         end
18     end
19     %-----Finding the rake face-----
20     [H, THETA, RHO] = hough(obj.BW, 'Theta', 81:85); %Hough transformation
21     P = houghpeaks(H, 10);
22     obj.lines = houghlines(obj.BW, THETA, RHO, P, 'FillGap', 15, 'MinLength'
,10); %Here we can find the lines of cutting edge and afterwards find the
coordinate of the tool tip
23     l = length(obj.lines);
24     obj.coordRF = [];
25     for i=1:l
26         Theta=obj.lines(i).theta;
27         t1 = obj.lines(i).point1;
28         t2 = obj.lines(i).point2;
29         rho = obj.lines(i).rho;
30         if rho < 103 && rho > 98
31             obj.coordRF = [t1;t2];
32             obj.RakeAngle = 90 - Theta;
33         end
34     end
35 end

```

Since the rake angle is 6° and the clearance is 3° ranges of [81:85] and [2:5] were given to each respectively, as it is seen on lines 4 and 20. Concerning about the rake angle, the range of angles is given by the complementary angles due to its reference in hough method. In this way, it taken the first 10 highlighted points in the accumulation matrix of hough process, which means the most reasonable points that may represent the edge lines.

The fixed position of tool allows also the predetermination of the ρ parameter, which is distance of the detected lines from the reference. This is also seen on lines 14 and 30 as boundary conditions to determine the right edge lines. The outputs of this function are the endings coordinates of the detected line and also the angle of the corresponding angular coefficient.

4.3.2.1 Rake and clearance face

With the data provided by the output of hough function, it is possible to extend the lines to match the entire rake and clearance edge. This is an important step of the analysis method because it allows to build an object (binary image) that is a mask to remove only

the region of interest, on this case the tool shape. Consequently, it will be possible analyze the temperature fields and thermal behavior in the tool without any interference of the temperatures in the vicinity.

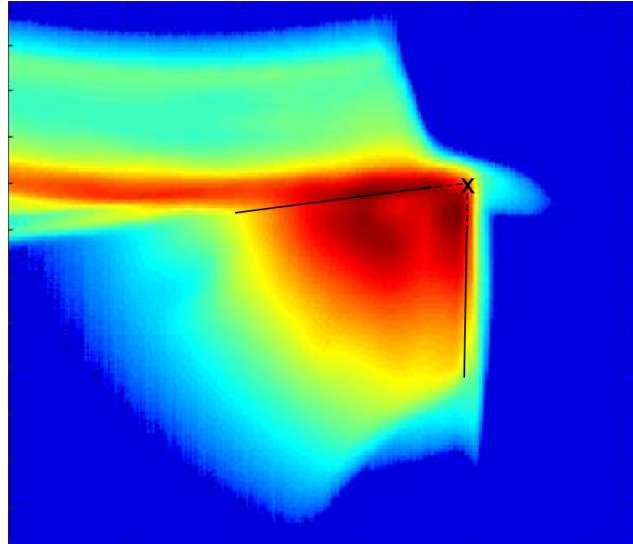


FIGURE 4.4 – Lines detected by hough transformation method

4.3.2.2 Tool tip coordinates

As the rake and clearance edges are determined, the tool tip will be calculated by means of the intersection between these lines. On the figure 4.4 the found lines are extended until they intersect, then the coordinates of tool tip can be calculated. It is important to determine these coordinates due to the interest in knowing the temperatures that the area close to the tip can reach, which is related directly with tool life and therefore the surface finish.

4.3.3 Maximum temperatures

As the code were able to segment the tool shape from the entire matrix, it gets easier to extract the other region of interest that present measurable range of temperatures, the chip. Getting the maximum temperature of each zone allows not only to know if the measured temperatures are inside the limit of measurement but also to compare the behavior of this maximum temperature of different cutting velocities and a_p .

4.3.4 Temperature fields

In this step, it will be used the other auxiliary function mentioned on the subsection Contour plot. This is an important function to determine same level curves, as the

isotherms inside the tool shape. The contour levels are determined in a step of 50 °C.

```
1 [C,h] = contour(obj.frame,v);
```

The output of contour function is a matrix C with 2 rows that will provide the levels of temperature and the number of coordinates followed by their absolute values of x and y, which are very valuable when comes to calculate heat flows.

```
C      = [C(1) C(2) C(3) ...C(k)... C(N)]
C(k)   = [level x(1) x(2) ...
          numxy y(1) y(2) ...]
```

For each matrix C(k), level shows which temperature it is representing and numxy is the amount of coordinates used to build the level. The coordinates are represented in the pair (x,y).

4.3.5 Heat flows - Chip and Tool

As described on section 3.2, the heat flow through tool and the energy carried away by chip are calculated. For heat flow through the tool, it is possible to extract isothermal lines by means of contour command and to calculate the gradient of temperatures, which already is normal to the isothermal lines due to its properties, with gradient command. The width is already known 3.1. The length of the chosen isotherm is done by counting the amount of pixels, provided by the coordinates in contour plot, and turned into millimeter with the scale factor afterwards. In the case of the energy carried away by chip, the chosen line is placed on the end of contact chip - tool. The explanation for it is that all the heat source in the friction zone is located before this line, in other words there is no other heat source after this line that could provide more thermal energy to be carried away by chip.

4.3.5.1 Heat partitions

Having the results of the subsection 3.2, these values can be combined with the total power (P) generated during the cutting process to calculate the energy that goes to the workpiece by means of energy balance (equation 3.7). Then, it is possible to calculate the heat partition relative to each zone of interest.

$$p_i = \frac{\dot{Q}_i}{P} \quad (4.1)$$

Which the index i is related to C (chip), W (workpiece) and T (tool).

5 Results

The total power produced along this high speed machining was calculated as in the equation 3.3, the values are shown on figure 5.1.

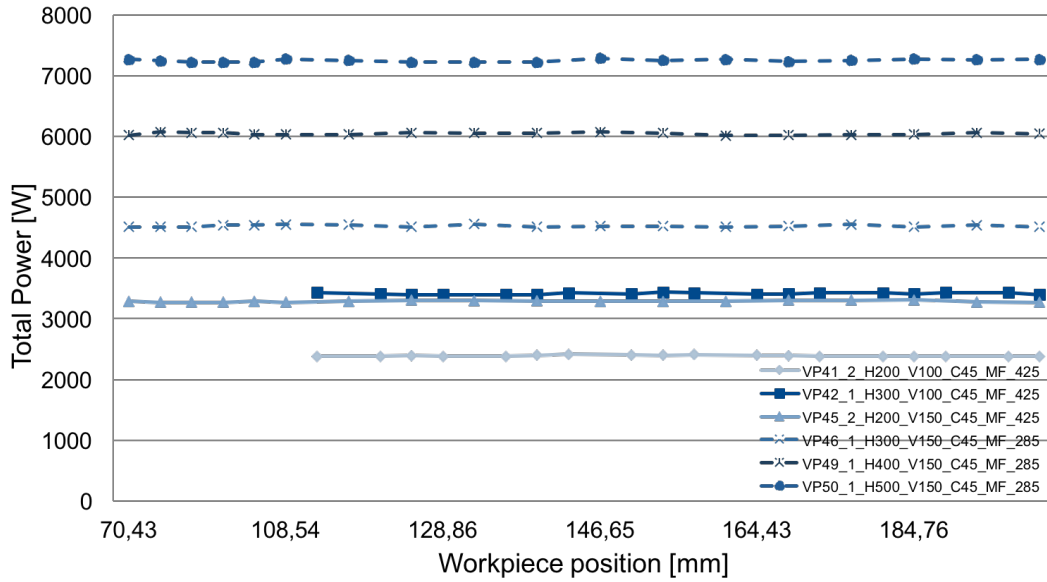


FIGURE 5.1 – Total power produced

As expected, the higher are the values of cutting velocity or depth of cut higher are the values of total power produced. For each experiment, the computational method was able to provide the thermal energy that goes to tool, chip and workpiece by means of energy balance. Then, it can be observed the thermal behavior of every area of interest along the workpiece position. The measurement starts when a reasonable area of the cutting zone reaches the minimum temperature. For cutting velocity of $150\text{m}/\text{min}$ it starts earlier because the rate of heat production is higher than when the cutting velocity is $100\text{m}/\text{min}$.

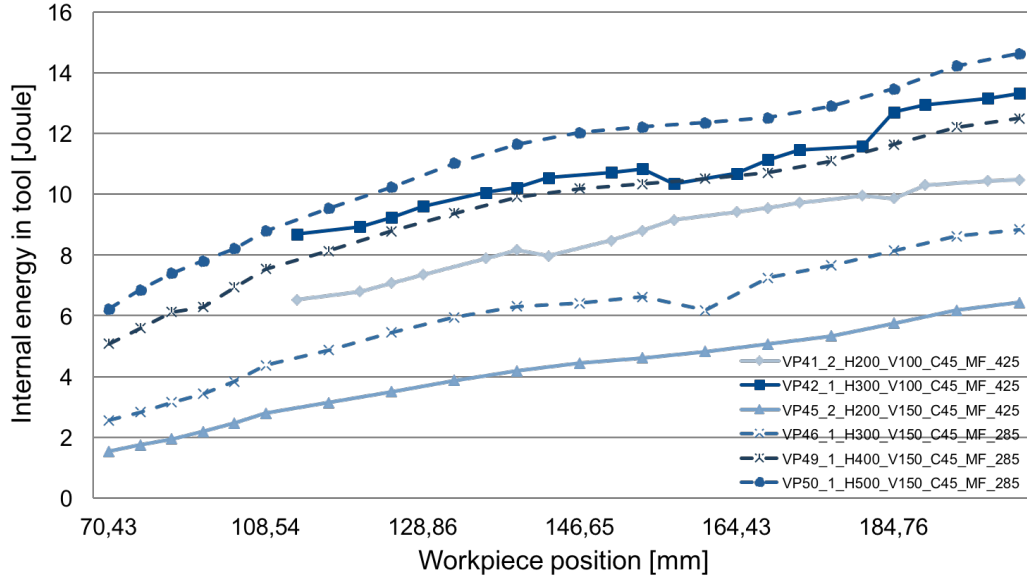


FIGURE 5.2 – Inner energy of tool along workpiece position

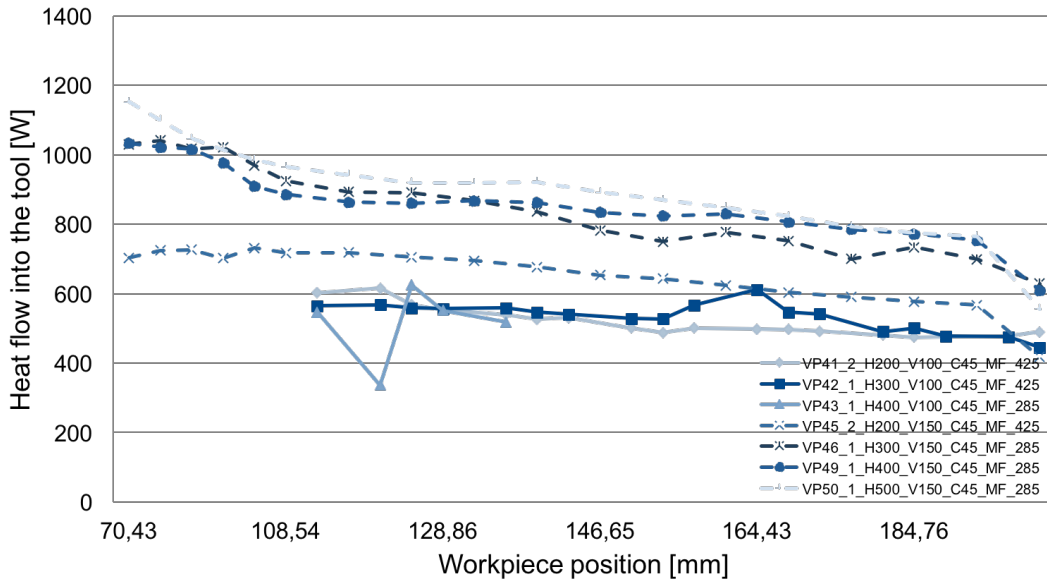


FIGURE 5.3 – Heat flow into tool

As it can be observed on the previous figure 5.3, the change rate of the inner energy of tool begins with a higher value than in the end of process. The rate starts to stabilize, indicating the beginning of the steady state.

To exemplify the results, it will be taken to represent the outcomes concerning heat partitions the experiment with cutting velocity $v_c = 150m/min$ and depth of cut $a_p = 500\mu m$. All the others experiments had approximately the same behavior during the cutting process. Concerning about the heat partition through tool, workpiece and the energy carried away by chip, their behaviors can be observed on the figure 5.4. There is a slight decrement in the heat flow through tool, which it was expected due to the steady

state as discussed before. As for the energy carried by chip, it may be noticed a slight increment.

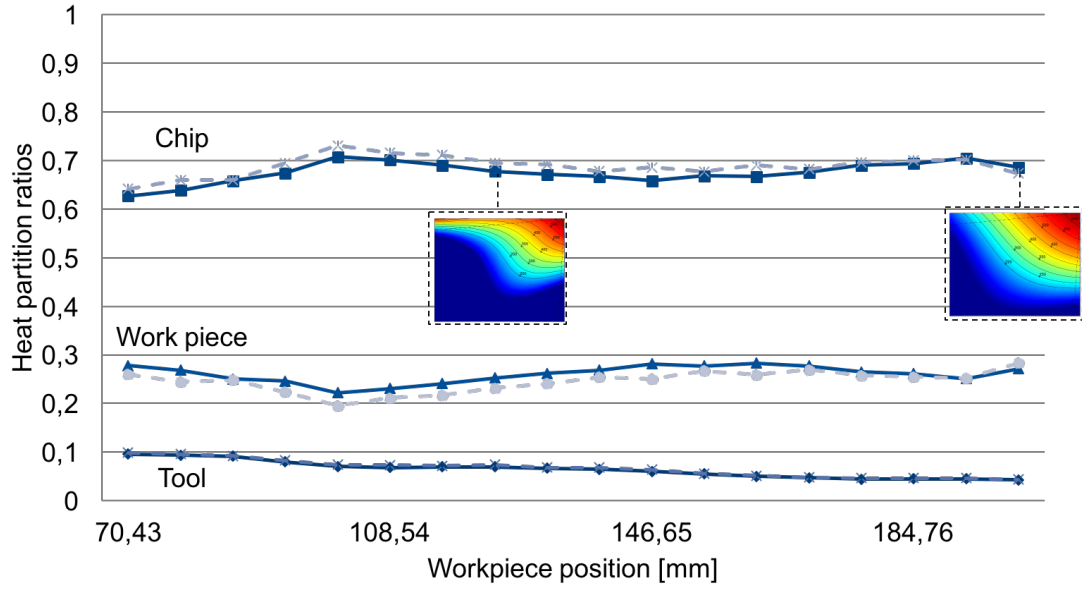


FIGURE 5.4 – Heat partition for experiment with $a_p = 500\mu\text{m}$ and $v_c = 150\text{ m/min}$

It is important to highlight the total power produced during the cutting process, which has a significant value because of the high values of cutting velocity and force. Also, it must be noticed the amount of energy that goes to chip (figure 5.5 and 5.6). The chip takes around 70% of the total energy produced, this fact may be explained due to the high temperatures that the region can reach and the high velocity of flowing.

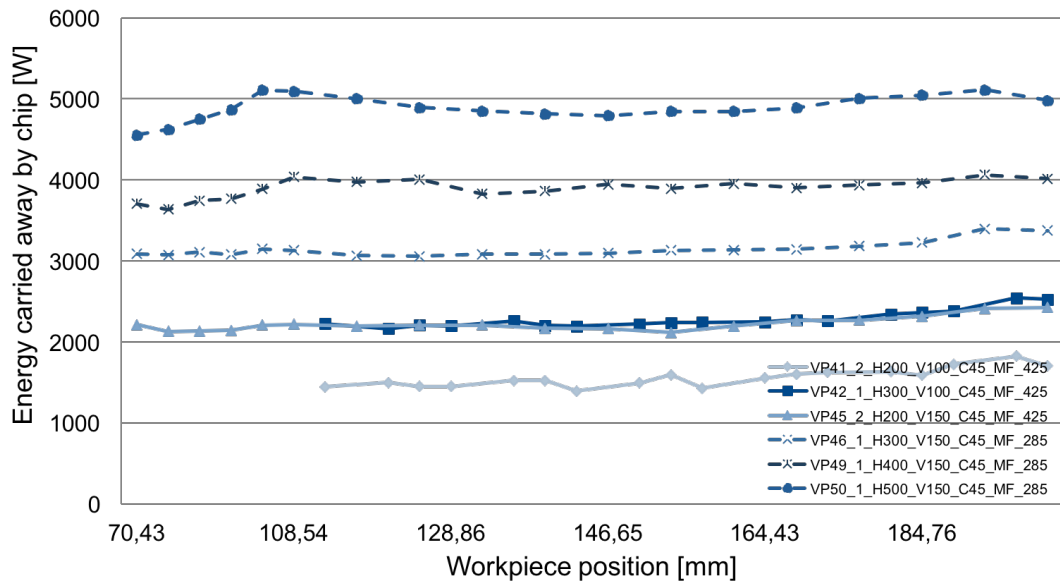


FIGURE 5.5 – Thermal energy into chip

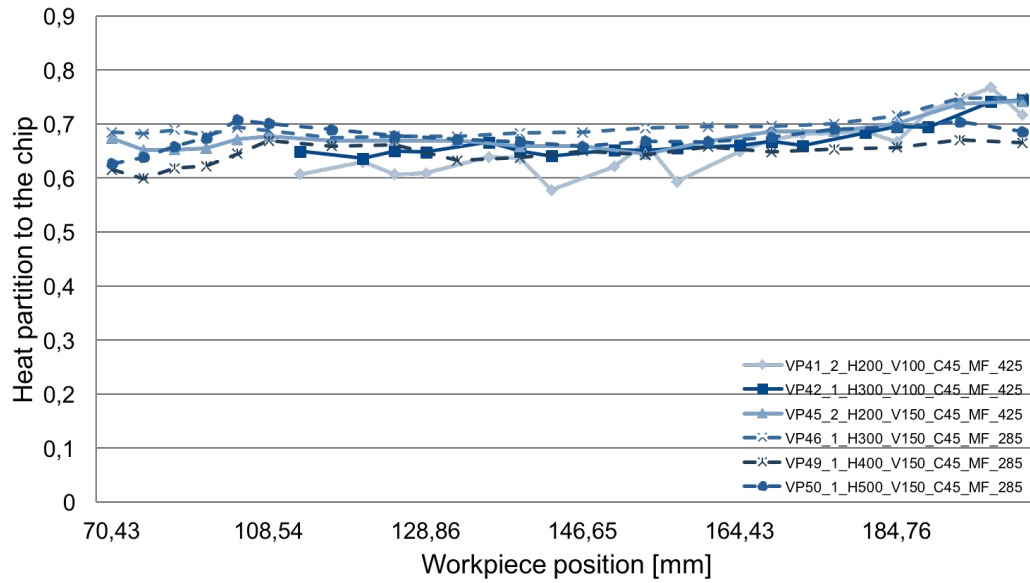


FIGURE 5.6 – Heat partition ratio for chip

As for the tool (figure 5.7), the partition of energy reaches a much smaller range when close to the steady state. The values of the partition to tool in this stage goes from 4% until 8%.

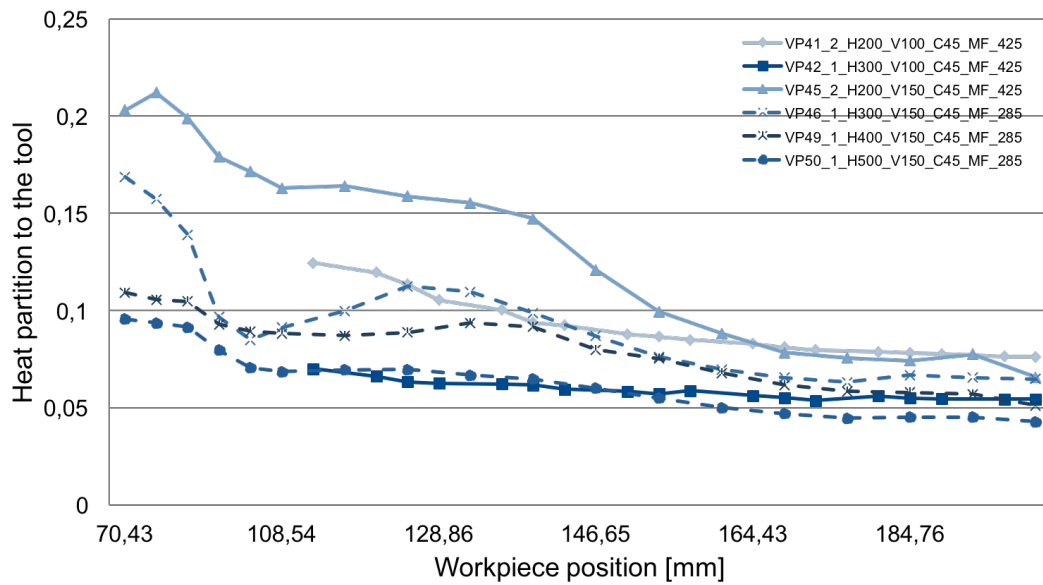


FIGURE 5.7 – Heat partition ratio for tool

6 Conclusion

The results found when processing thermal images provided a reasonable understanding about heat distribution through tool and chip components. Most of the heat generated during the cutting process goes to dissipation on the removed chip, about 70% of the total power generated. Most part of the data provided by the cutting process regards to transient state, but is also possible to note it reaching the steady state close to the end of the cutting process, which suggests that this computational method also may be extended for this part of the process.

One of the problems to elaborate this work was that many of the videos were damaged due to pieces of chip interfering on the ideal presentation of each thermal frame. Pieces of chip with different temperatures were captured on tool surface, disturbing the field of temperature along the tool shape. This fact made impossible the use of some frames from the same video and entire other experiments sometimes.

It may be noticed that for experiments with the same relation $v_c \times a_p$ (figure 5.5) seems to provide the same energy to be carried by the flowing chip. Since the thermography method is very sensible to external interference and many experiments were damaged as mentioned before, it would be necessary to perform new experiments to validate this hypothesis.

The thermography method for temperatures measurement still presents some challenges, mainly when comes to set the correct emissivity. Although it still takes a reasonable effort to determine the right emissivity for accomplishing a reliable measurement, the thermography is a powerful tool for inspection, specially for cutting processes as discussed in this paper. With a filter of camera capable of measure temperatures lower than 200 Celsius degrees, it would be possible to complete the study with the measurement of temperatures on the workpiece area, providing more results.

Computer vision, as image recognition patterns and image processing, is being used each time more nowadays processes. For a future study beyond this paper, computer vision can become an even stronger tool when combined with machine learning, which is revolutionizing manufacturing and medical areas for example. The principles used to build this computational method could be converted to analyze others types of cutting

processes, as milling. Then, it could be turned into an intelligent system to support machining processes, improving all cutting parameters in order to obtain higher efficiency of tool, increasing tool life, better surface finishing of the workpiece and lower cutting time.

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Appendix A - Source Code

A.1 Temperature Analysis

```
1 classdef TemperatureAnalyze
2     % This class was built to analyze the temperature inside the tool
3     % shape, the temperature gradient, the isotherms...
4
5     properties(GetAccess = 'public', SetAccess = 'private')
6         CoordinateToolTip;
7         TemperatureToolTip;
8         RakeAngle;%Rake face slope
9         ClearanceAngle;%Clearance face slope
10        ShearAngle;
11        FrictionAngle;
12        MeanTemperatureTool;
13        MaximumTemperatureTool;
14        MaximumTemperatureChip;
15        MaximumTemperatureCuttingZone;
16        HeatCarriedAwayByChip;
17        HeatFluxAwayFromToolTip;
18        HeatFluxThroughWorkpiece;
19        TotalPowerBalance;
20        InternalEnergyTool;
21        CuttingForcePowerDirection;
22        CuttingForceUncutChipThicknessDirection;
23        CuttingForceParallelToolFace;
24        CuttingForceParallelShearPlane;
25        CuttingForcePerpendicularShearPlane;
26        CuttingForcePerpendicularToolFace;
27        CoefficientFriction;
28        ShearStress;
29        NormalStress;
30        PecletNumber;
31        RatioR;
32        ShearEnergyVolume;
33        FrictionEnergyVolume;
34        CuttingVelocity;
35        UnCutChipThickness;
36        ContactLength;
37    end
38
39    properties(GetAccess = 'private', SetAccess = 'private')
40        coordRF;
41        coordCF;
42        BW;
43        lines;
44        frame;
45        pointCF;%auxiliar to plot the cutting edge
46        pointRF;
47        pointM;
48        Tx;%auxiliar to plot the gradients of the frame
49        Ty;
50        biImageTool;%Binary image of the tool shape
51        biImageChip;
```

```

52     biShearLine;
53     xyMaxTemp;%coordinates of the point inside the chip with maximum Temperature
54     lineChip;
55     lineTool;
56     validTemperature;
57     heatCapacity;
58     nExcPoints;
59     heatAccumulatedPerLine;
60     ptosLines;
61     extPtosLineChip;
62     line200;
63 end
64
65 methods
66     % methods, including the constructor are defined in this block
67
68     function obj = TemperatureAnalyze2(Frame,index)%constructor
69         %Inputs -----
70         Fp = 3220;%Cutting force in the power direction (Newtons)
71         Fq = 1120;%Passive force (Newtons)
72         widthTool = 4.4*10^-3;%meters
73         Vp = 150/60;%meters/second
74         tuc = 500*10^-6;%meters
75         clength = 0.00251;%Define as an empty vector if we do not have
76         %the mean value
77         tt = [197 78];
78         obj.validTemperature = 200;% For any experiment
79         A = 0.1;%percentage of the deformation energy that is converted in heat
80         %-----
81         obj.CuttingVelocity = Vp*60;%m/minute
82         obj.UnCutChipThickness = tuc;
83         obj.frame = Frame(index).f;
84         if isequal(clength,[])
85             clength = obj.contactLength();
86         end
87         obj.ContactLength = clength;
88         % obj = obj.calculateCoordinates();
89         % if isempty(obj.coordRF)==0 && isempty(obj.coordCF)==0
90         % % obj = obj.coordinateToolTip();
91         % else %Default conditions
92         % if isempty(obj.coordRF)
93         % obj.RakeAngle = 6;
94         % end
95         % if isempty(obj.coordCF)
96         % obj.ClearanceAngle = 3;
97         % end
98         % end
99         obj.CoordinateToolTip = tt;
100         obj.ClearanceAngle = 3;
101         obj.RakeAngle = 6;
102         obj.frame = Frame(index).f;
103         obj = obj.toolContour();
104         obj = obj.findLineTool();
105         obj = obj.chipContour();
106         obj = obj.findLineChip();
107         obj = obj.pointsRFandCF();
108         obj = obj.TempTT();
109         obj = obj.meanTemperatureTool();
110         obj = obj.maxTemperatureTool();
111         obj = obj.maximumTemperature();
112         obj = obj.maxTemperatureChip();
113         obj = obj.calculateGradient();
114         obj = extremePointsChip(obj);
115         obj = obj.heatBalance(tuc,Vp,widthTool);
116         obj = obj.internalEnergyTool(widthTool);
117         obj = obj.shearLine();
118         obj = obj.calculatePecletNumber();
119         obj = obj.forcesValues(Fp,Fq,widthTool,tuc);
120         obj.TotalPowerBalance = 0.97*(obj.CuttingVelocity*(obj.
CuttingForcePowerDirection*(1-A) + obj.CuttingForceParallelToolFace*A*obj.RatioR

```

```

    )/60);
121     obj.HeatFluxThroughWorkpiece = obj.TotalPowerBalance - obj.
HeatCarriedAwayByChip - obj.HeatFluxAwayFromToolTip;
122     end
123
124     function obj = framesOverlap(obj,Frame,index)
125         cTT = obj.CoordinateToolTip;
126         alpha = (90 - obj.ClearanceAngle)*pi/180;
127         gamma = obj.RakeAngle*pi/180;
128         p1 = cTT + 67*[-cos(gamma) sin(gamma)];
129         p2 = cTT + 33*[-cos(alpha) sin(alpha)];
130         c = [cTT(1) p1(1) p2(1)];
131         r = [cTT(2) p1(2) p2(2)];
132         biTool70 = roipoly(Frame(index).e70,c,r);
133         aux = biTool70 == 1 & obj.biImageChip == 1;
134         biTool70 = biTool70 - aux;
135         biTool70andChip = biTool70 == 1 | obj.biImageChip == 1;
136         biFrame85 = ones(size(Frame(index).e85)) - biTool70andChip;
137         obj.frame = biTool70andChip.*Frame(index).e70 + biFrame85.*Frame(index).
e85;
138     end
139
140     function obj = toolContour(obj)
141         A = round(obj.CoordinateToolTip);
142         m = size(obj.frame,1);
143         xt = A(1);
144         yt = A(2);
145         y1 = round(yt + (xt - 1)*tan(obj.RakeAngle*pi/180));
146         x2 = round(xt - (m - yt)*tan(pi/2 - (90 - obj.ClearanceAngle)*pi/180));
147         c = [xt 0 0 x2];
148         r = [yt y1 m m];
149         B = roipoly(obj.frame,c,r);
150         obj.biImageTool = B;
151     end
152
153     function obj = chipContour(obj)
154         c = obj.line200(1,:);
155         r = obj.line200(2,:);
156         B = roipoly(obj.frame,c,r);
157         obj.biImageChip = B;
158         B2 = obj.biImageTool == 1 & B == 1;
159         B = B - B2;
160         obj.biImageChip = B;
161     end
162
163     function obj = maximumTemperature(obj)
164         obj.MaximumTemperatureCuttingZone = max(max(obj.frame));
165         [~,lin] = max(obj.frame);
166         [~,col] = max(max(obj.frame));
167         lin = lin(col);
168         obj.xyMaxTemp = [col lin];
169     end
170
171     function l = contactLength(obj)
172         imagesc(obj.frame)
173         imdistline%Help to measure the amount of pixels on the contact length
174         v = input('What is the value of the contact length for this frame? ');
175         close all
176         l = 15*10^-6*v;
177     end
178
179     function obj = maxTemperatureTool(obj)
180         C = obj.biImageTool;
181         Frame = C.*obj.frame;
182         T = max(max(Frame));
183         obj.MaximumTemperatureTool = T;
184     end
185
186     function obj = maxTemperatureChip(obj)
187         Frame = obj.biImageChip.*obj.frame;

```

```

188     obj.MaximumTemperatureChip = max(max(Frame));
189 end
190
191 function obj = meanTemperatureTool(obj)
192     B = obj.biImageTool;
193     Frame = B.*obj.frame;
194     B = Frame > obj.validTemperature;
195     Frame = B.*Frame;
196     s = sum(sum(Frame));
197     n = sum(sum(B));
198     meanT = s/n;
199     obj.MeanTemperatureTool = meanT;
200 end
201
202 function obj = displayBinary(obj)
203     imshow(obj.BW);
204     hold on
205     plot(obj.coordRF(:,1),obj.coordRF(:,2),'bx')
206     plot(obj.coordCF(:,1),obj.coordCF(:,2),'yx')
207     plot(obj.CoordinateToolTip(1),obj.CoordinateToolTip(2),'xm')
208     hold off
209 end
210
211 function obj = TempTT(obj)
212     p1 = round(obj.CoordinateToolTip + 5*[-cos(obj.RakeAngle*pi/180) sin(obj
.RakeAngle*pi/180)]);
213     p2 = round(obj.CoordinateToolTip + 5*[-cos((90 - obj.ClearanceAngle)*pi
/180) sin((90 - obj.ClearanceAngle)*pi/180)]);
214     p3 = round(obj.CoordinateToolTip + 5*[-(cos(obj.RakeAngle*pi/180)+cos
((90 - obj.ClearanceAngle)*pi/180)) (sin(obj.RakeAngle*pi/180)+sin((90 - obj
.ClearanceAngle)*pi/180))]);
215     T1 = obj.frame(p1(2),p1(1));
216     T2 = obj.frame(p2(2),p2(1));
217     T3 = obj.frame(p3(2),p3(1));
218     TT = obj.frame(round(obj.CoordinateToolTip(2)),round(obj
.CoordinateToolTip(1)));
219     T = [T1 T2 T3 TT];
220     obj.TemperatureToolTip = mean(T);
221 end
222
223 function obj = calculateCoordinates(obj)
224     obj.BW = edge(obj.frame,'sobel');
225     %-----Finding the clearance face-----
226     [H, THETA, RHO] = hough(obj.BW,'Theta',2:5);%Hough transformation
227     P = houghpeaks(H, 10);
228     obj.lines = houghlines(obj.BW, THETA, RHO, P, 'FillGap', 15,'MinLength'
,10);%Here we can find the lines of cutting edge and afterwards find the
coordinate of the tool tip
229     l = length(obj.lines);
230     obj.coordCF = [];
231     for i=1:l
232         Theta = obj.lines(i).theta;
233         t1 = obj.lines(i).point1;
234         t2 = obj.lines(i).point2;
235         rho = obj.lines(i).rho;
236         if rho < 204 && rho > 198
237             obj.coordCF = [t1;t2];
238             obj.ClearanceAngle = Theta;
239         end
240     end
241     %-----Finding the rake face-----
242     [H, THETA, RHO] = hough(obj.BW,'Theta',81:85);%Hough transformation
243     P = houghpeaks(H, 10);
244     obj.lines = houghlines(obj.BW, THETA, RHO, P, 'FillGap', 15,'MinLength'
,10);%Here we can find the lines of cutting edge and afterwards find the
coordinate of the tool tip
245     l = length(obj.lines);
246     obj.coordRF = [];
247     for i=1:l
248         Theta=obj.lines(i).theta;

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```

249         t1 = obj.lines(i).point1;
250         t2 = obj.lines(i).point2;
251         rho = obj.lines(i).rho;
252         if rho < 103 && rho > 98
253             obj.coordRF = [t1;t2];
254             obj.RakeAngle = 90 - Theta;
255         end
256     end
257 end
258
259 function obj = coordinateToolTip(obj)
260     a = (obj.coordRF(1,2)-obj.coordRF(2,2))/(obj.coordRF(1,1)-obj.coordRF
(2,1));%The slope of the rake face hardly will be Inf(Infinite) or NaN(Not-a-
number),
261     %because we took for this face a slope smaller than 45
262     b = obj.coordRF(1,2)-a*obj.coordRF(1,1);
263     m = (obj.coordCF(1,2)-obj.coordCF(2,2))/(obj.coordCF(1,1)-obj.coordCF
(2,1));%Slope of the cf, in some cases may be Inf(inclination of 90?, for
example)
264     h = @(x) (a*x+b);%line of the clearance face represented by f
265     if m == Inf || m == -Inf%if the slope of the cf is 90? or -90?(Inf or -Inf
)
266         xi = obj.coordCF(1,1);%xi represents the coordinate x of the
intersection(tool tip)
267     else
268         n = obj.coordCF(1,2)-m*obj.coordCF(1,1);
269         xi = (n-b)/(a-m);
270     end
271     yi = h(xi);
272     obj.CoordinateToolTip = [xi yi];
273 end
274
275 function obj = displayImageAndToolTip(obj)
276     figure
277     imagesc(obj.frame);
278     hold on
279     plot(obj.CoordinateToolTip(1),obj.CoordinateToolTip(2),'xm')
280     hold off
281 end
282
283 function obj = pointsRFandCF(obj)
284     alpha = (90 - obj.ClearanceAngle)*pi/180;
285     gamma = obj.RakeAngle*pi/180;
286     obj.pointRF = obj.CoordinateToolTip + 90*[-cos(gamma) sin(gamma)];
287     obj.pointCF = obj.CoordinateToolTip + 90*[-cos(alpha) sin(alpha)];
288     obj.pointM = obj.CoordinateToolTip + 40*[-2*cos(alpha)-cos(gamma) 2*sin(
alpha)+sin(gamma)];
289 end
290
291 function vT = temperatureRFandCF(obj)
292     pixelpitch = 15*10^-3;% mm/pixel
293     extCF = obj.pointCF;% final point on the clearance face
294     extRF = obj.pointRF;% final point on the rake face
295     extM = obj.pointM;
296     l1 = round(abs(obj.CoordinateToolTip(1)-extRF(1)));%length in pixels
rake line
297     l2 = round(abs(obj.CoordinateToolTip(2)-extCF(2)));%length in pixels
clearance line
298     l3 = max(round(abs(obj.CoordinateToolTip-extM)));
299     vRFx = round(linspace(obj.CoordinateToolTip(1),extRF(1),l1));%
coordinates x of the rake line
300     vRFy = round(linspace(obj.CoordinateToolTip(2),extRF(2),l1));%
coordinates y of the rake line
301     vCFx = round(linspace(obj.CoordinateToolTip(1),extCF(1),l2));%
coordinates x of the clearance line
302     vCFy = round(linspace(obj.CoordinateToolTip(2),extCF(2),l2));%
coordinates y of the clearance line
303     vMx = round(linspace(obj.CoordinateToolTip(1),extM(1),l3));
304     vMy = round(linspace(obj.CoordinateToolTip(2),extM(2),l3));

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```

305     T_RF = zeros(1,11);%temperature for each pixel (each coordinate pair) -
rake line
306     T_CF = zeros(1,12);%temperature for each pixel (each coordinate pair) -
clearance line
307     T_M = zeros(1,13);
308     for t=1:11
309         T_RF(t) = obj.frame(vRFy(t),vRFx(t));%Building the temperature
vector - rake line
310     end
311     for t=1:12
312         T_CF(t) = obj.frame(vCFy(t),vCFx(t));%Building the temperature
vector - clearance line
313     end
314     for t=1:13
315         T_M(t) = obj.frame(vMy(t),vMx(t));%Building the temperature vector -
clearance line
316     end
317     d1 = zeros(1,11);%distance for each pixel along the line
318     d2 = zeros(1,12);
319     d3 = zeros(1,13);
320     for t=1:11 - 1
321         d1(t+1)=(((vRFx(t+1)-vRFx(1))^2)+((vRFy(t+1)-vRFy(1))^2))^(1/2);
322     end
323     for t=1:12 - 1
324         d2(t+1)=(((vCFx(t+1)-vCFx(1))^2)+((vCFy(t+1)-vCFy(1))^2))^(1/2);
325     end
326     for t=1:13 - 1
327         d3(t+1)=(((vMx(t+1)-vMx(1))^2)+((vMy(t+1)-vMy(1))^2))^(1/2);
328     end
329     d1 = d1*pixelpitch;
330     d2 = d2*pixelpitch;
331     d3 = d3*pixelpitch;
332     figure
333     hold on
334     plot(d1,T_RF)
335     plot(d2,T_CF)
336     plot(d3,T_M)
337     xlabel('Distance from the tool tip (mm)')
338     ylabel('Temperature (?C)')
339     legend('Rake face','Clearance face','Middle vector')
340     hold off
341     figure
342     imagesc(obj.frame)
343     colormap jet
344     hold on
345     plot(vRFx,vRFy,'k','LineWidth',1)
346     plot(vCFx,vCFy,'k','LineWidth',1)
347     plot(vMx,vMy,'k','LineWidth',1)
348     hold off
349     m = min([l1 l2 l3]);
350     vT = [d1(1:m)' T_RF(1:m)' d2(1:m)' T_CF(1:m)' d3(1:m)' T_M(1:m)'];
351 end
352
353 function obj = extremePointsChip(obj)
354     [y,x] = find(obj.lineChip);
355     obj.extPtosLineChip = [x(1) y(1);x(end) y(end)];
356 end
357
358 function obj = displayIsotherms(obj)
359     tRF = obj.RakeAngle*pi/180;
360     tCF = (90 - obj.ClearanceAngle)*pi/180;
361     vRF = [-cos(tRF) sin(tRF)];
362     vCF = [-cos(tCF) sin(tCF)];
363     %p1 RF direction
364     t = (obj.CoordinateToolTip(1) - 1)/vRF(1);
365     p1 = obj.CoordinateToolTip - t*vRF;
366     %p2 CF direction
367     t = (256 - obj.CoordinateToolTip(2))/vCF(2);
368     p2 = obj.CoordinateToolTip + t*vCF;
369     %auxiliar to plot

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370     auxX = [p1(1) obj.CoordinateToolTip(1) p2(1)]';
371     auxY = [p1(2) obj.CoordinateToolTip(2) p2(2)]';
372     Tmax = max(max(obj.biImageTool.*obj.frame));
373     Tv = obj.validTemperature;
374     v = round(Tv:40:Tmax);
375     %Display tool and isotherms-----
376     lc = obj.extPtosLineChip;
377     figure
378     imagesc(obj.frame)
379     colormap jet
380     hold on
381     plot(auxX,auxY,'k')
382     plot(lc(:,1),lc(:,2),'k--','LineWidth',1)
383     [C,h] = contour(obj.frame,v);
384     h.LineColor = [0.247 0.247 0.247];
385     clabel(C,h,'manual','FontSize',10);
386     x = obj.CoordinateToolTip(1);
387     y = obj.CoordinateToolTip(2);
388     axis([x-180 x+15 y-60 y+130])
389     cb = colorbar('vert');
390     zlab = get(cb,'ylabel');
391     set(zlab,'String','Temperature (?C)');
392     cb.Limits = [0 450];
393     cb.FontSize = 10;
394     zlab.FontSize = 10;
395     daspect([1,1,1])
396     ax = gca;
397     v = [0.2 0.6 1.0 1.4 1.8 2.2 2.6];
398     vt = v/0.015;
399     vx = x + 15 - vt;
400     ax.XTick = fliplr(vx);
401     ax.XTickLabel = fliplr(v);
402     ax.XAxisLocation = 'top';
403     vy = y - 60 + vt;
404     ax.YTick = vy;
405     ax.YTickLabel = v;
406     ax.YAxisLocation = 'right';
407     xlabel('millimeters')
408     ylabel('millimeters')
409     hold off
410 end
411
412 function obj = calculateGradient(obj)
413     pp = 15*10^-6;
414     tx = zeros(size(obj.frame));
415     ty = zeros(size(obj.frame));
416     k = 0;
417     for j = 1:5
418         [auxx,auxy]=gradaux_v2(obj.frame,j);
419         tx = tx + auxx;
420         ty = ty + auxy;
421         k = k + 1;
422     end
423     obj.Tx = tx/(k*pp);
424     obj.Ty = ty/(k*pp);
425 end
426
427 function obj = displayGradient(obj)
428     auxx = [obj.pointCF(1) obj.CoordinateToolTip(1) obj.pointRF(1)];
429     auxy = [obj.pointCF(2) obj.CoordinateToolTip(2) obj.pointRF(2)];
430     k = 75.4;
431     qx = -k*obj.Tx;
432     qy = -k*obj.Ty;
433     figure
434     quiver(qx,qy)
435     hold on
436     plot(auxx,auxy,'k')
437     xmin = obj.CoordinateToolTip(1) - 10;
438     xmax = obj.CoordinateToolTip(1) + 5;
439     ymin = obj.CoordinateToolTip(2) - 5;

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```

440     ymax = obj.CoordinateToolTip(2) + 10;
441     axis([xmin xmax ymin ymax])
442     title('Tool Tip')
443     daspect([1,1,1])
444     figure
445     quiver(qx,qy)
446     hold on
447     plot(auxx,auxy,'k')
448     xmin = obj.CoordinateToolTip(1) - 30;
449     xmax = obj.CoordinateToolTip(1) - 10;
450     ymin = obj.CoordinateToolTip(2) - 5;
451     ymax = obj.CoordinateToolTip(2) + 15;
452     axis([xmin xmax ymin ymax])
453     title('Rake Face')
454     daspect([1,1,1])
455     figure
456     quiver(qx,qy)
457     hold on
458     plot(auxx,auxy,'k')
459     xmin = obj.CoordinateToolTip(1) - 10;
460     xmax = obj.CoordinateToolTip(1) + 10;
461     ymin = obj.CoordinateToolTip(2) + 10;
462     ymax = obj.CoordinateToolTip(2) + 20;
463     axis([xmin xmax ymin ymax])
464     title('Clearance Face')
465     daspect([1,1,1])
466 end
467
468 function obj = displayGradientContour(obj)
469     auxx = [obj.pointCF(1) obj.CoordinateToolTip(1) obj.pointRF(1)];
470     auxy = [obj.pointCF(2) obj.CoordinateToolTip(2) obj.pointRF(2)];
471     k = 75.4;
472     qx = -k*obj.Tx;
473     qy = -k*obj.Ty;
474     figure
475     quiver(qx,qy)
476     hold on
477     plot(auxx,auxy,'k')
478     contour(obj.frame,10)
479     xmin = obj.CoordinateToolTip(1) - 20;
480     xmax = obj.CoordinateToolTip(1) + 5;
481     ymin = obj.CoordinateToolTip(2) - 5;
482     ymax = obj.CoordinateToolTip(2) + 20;
483     axis([xmin xmax ymin ymax])
484     daspect([1,1,1])
485 end
486
487 function obj = findLineChip(obj)
488     [m,n] = size(obj.frame);
489     o = obj.RakeAngle*pi/180;
490     l = obj.ContactLength/(15*10^-6);
491     c = obj.CoordinateToolTip + l*[-cos(o) sin(o)];
492     xm = c(1);
493     ym = c(2);
494     x1 = xm - tan(o)*(ym - 1);
495     x2 = x1 + tan(o)*(m - 1);
496     vx = round(linspace(x1,x2,m));
497     vy = linspace(1,m,m);
498     B1 = zeros(m,n);
499     for i = 1:m
500         B1(vy(i),vx(i)) = 1;
501     end
502     B2 = B1 == 1 & obj.biImageChip == 1;
503     obj.lineChip = B2;
504 end
505
506 function obj = findLineTool(obj)
507     [m,n] = size(obj.frame);
508     Tmax = max(max(obj.biImageTool.*obj.frame));
509     Tv = obj.validTemperature;

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```

510     v = round(Tv:40:Tmax);
511     if length(v) == 1
512         v = round([Tv Tmax]);
513     end
514     [C,~] = contour(obj.frame,v);
515     close
516     l = length(v);
517     B = zeros(m,n,l);
518     C = round(C);
519     for k = 1:l
520         [~,J] = find(C == v(k));
521         [~,p] = max(C(2,J));
522         J = J(p);
523         for z = J+1:J+C(2,J)
524             B(C(2,z),C(1,z),k) = 1;
525         end
526         if k == 1
527             obj.line200 = C(:,J+1:J+C(2,J));
528         end
529         B(:, :, k) = B(:, :, k).*obj.biImageTool;
530     end
531     obj.lineTool = B;
532 end
533
534 function obj = heatBalance(obj,tuc,Vc,w)
535     k = 75.4;%heat conductivity
536     pp = 15*10^-6; %pixel pitch
537 %-----
538     %First part - Heat carried away by the chip
539     cp = [-4.39956806034758e-07 0.000707314520321484...
540         -0.0488770693887544 481.214007868631]; %AISI 1045
541     %Heat capacity for the workpiece
542     M = obj.lineChip.*obj.frame;
543     MH = polyval(cp,M);
544     MH(MH == cp(4)) = 0;
545     Ht = MH.*(obj.frame-22);%J/kg - 22 is the temperature of the environment
546     Ht = sum(sum(Ht));
547     n = sum(sum(obj.lineChip));
548     Hc = Ht/n; %mean entalpy on the line chip
549     % Vchip = 100*200/(60*n*15);
550     p = 7874; %kg/m^3
551     Qc = Hc*Vc*tuc*p;%Vc*tuc is the same for Vchip*tchip
552     obj.HeatCarriedAwayByChip = Qc*w;
553 %-----
554     %Second part - Heat carried away by the tool
555     dT = ((obj.Tx).^2 + (obj.Ty).^2).^(1/2);
556     Q = zeros(size(obj.lineTool,3),1);
557     for i = 1:size(obj.lineTool,3)
558         L = obj.lineTool(:, :, i);
559         Q(i) = sum(sum(L.*dT))*pp*w*k;
560     end
561     obj.heatAccumulatedPerLine = Q;
562     Qm = mean(Q(1:2));
563     obj.HeatFluxAwayFromToolTip = Qm;
564 end
565
566 function n = exceedingPoints(obj, Temperature)
567     B = obj.frame.*obj.biImageTool > Temperature;
568     n = sum(sum(B));
569 end
570
571 function obj = internalEnergyTool(obj,w)
572     pp = 15*10^-4;%in cm
573     cp = [2.50542895559373e-10 -1.99579761670655e-06 0.00274369536032376
574         3.09265830398264];%J/(K*cm3)
575     %Heat capacity for tool
576     Te = 22;
577     B = obj.frame.*obj.biImageTool > obj.validTemperature;
578     B1 = obj.frame.*B;
579     B2 = polyval(cp,B1);%Heat capacity for each pixel (J/kgK)

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579         B2(B2 == cp(4)) = 0;
580         H = B2.*(obj.frame - Te)*(pp^2)*100;%Heat Amount for each pixel(J/m)
581         Ha = sum(sum(H));%Mean value for the entire tool
582         obj.InternalEnergyTool = Ha*w;
583     end
584
585     function B = passBinaryImageTool(obj)
586         B = obj.biImageTool;
587     end
588
589     function B = passBinaryImageChip(obj)
590         B = obj.biImageChip;
591     end
592
593     function obj = shearLine(obj)
594         B = obj.biImageChip;
595         v1 = sum(B);
596         v1(v1 == 0) = [];
597         l1 = length(v1);
598         C = imcrop(B,[20 20 l1 100]);
599         [m,n] = size(C);
600         pto = zeros(1000,2);
601         count = 1;
602         for i = 2:m-1
603             for j = 2:n-1
604                 if C(i,j+1) == 1 && C(i,j-1) == 1 && C(i+1,j) == 1 && C(i-1,j)
== 1
605                     pto(count,:) = [i j];
606                     count = count + 1;
607                 end
608             end
609         end
610         for i = 1000:-1:1
611             if isequal(pto(i,:),[0 0]) == 1
612                 pto(i,:) = [];
613             end
614         end
615         l = size(pto,1);
616         for i = 1:l
617             C(pto(i,1),pt0(i,2)) = 0;
618         end
619
620         [H, THETA, RHO] = hough(C,'Theta',-40:-30);%Hough transformation
621         P = houghpeaks(H, 5);
622         lin = houghlines(C, THETA, RHO, P, 'FillGap', 15,'MinLength',10);
623         l=length(lin);
624         p1 = [];
625         p2 = [];
626         for i=1:l
627             Theta=lin(i).theta;
628             t1 = lin(i).point1;
629             t2 = lin(i).point2;
630             y = abs(t1(2)-t2(2));
631             if isempty(p1) && isempty(p2) && abs(Theta + 34) < 5
632                 p1 = t1 + [19 19];
633                 p2 = t2 + [19 19];
634                 ym = y;
635                 obj.ShearAngle = abs(Theta);
636             end
637             if abs(Theta + 34) < 5 && y > ym
638                 p1 = t1 + [19 19];
639                 p2 = t2 + [19 19];
640                 obj.ShearAngle = abs(Theta);
641             end
642         end
643         if isempty(obj.ShearAngle)
644             obj.ShearAngle = 30;
645         end
646     end
647

```

```

648     function obj = forcesValues(obj,Fp,Fq,w,tuc)
649         phi = obj.ShearAngle*pi/180;%shear angle
650         gamma = obj.RakeAngle*pi/180;%Rake angle
651         Fs = Fp*cos(phi) - Fq*sin(phi);%Cutting force component parallel to
shear plane
652         Ns = Fq*cos(phi) + Fp*sin(phi);%Cutting force component perpendicular to
shear plane
653         Fc = Fp*sin(gamma) + Fq*cos(gamma);%Cutting force component parallel to
tool face
654         Nc = Fp*cos(gamma) - Fq*sin(gamma);%Cutting force component
perpendicular to tool face
655         mu = Fc/Nc; % coefficient of friction
656         As = w*tuc/sin(phi);%Area shear plane
657         tau = Fs/As;%shear stress
658         sigma = Ns/As;%Normal stress
659         r = sin(phi)/cos(phi - gamma); %ratio r = t/tc = lc/l
660         ss = cos(gamma)/(sin(phi)*cos(phi-gamma));%shear strain
661         us = tau*ss;%shear energy per volume
662         uf = Fc*r/(tuc*w);%friction energy per volume
663         beta = atan(Fc/Nc);%friction angle on tool face
664         obj.CuttingForceParallelToolFace = Fc;
665         obj.CuttingForcePowerDirection = Fp;
666         obj.CuttingForceUncutChipThicknessDirection = Fq;
667         obj.CuttingForceParallelShearPlane = Fs;
668         obj.CuttingForcePerpendicularShearPlane = Ns;
669         obj.CuttingForcePerpendicularToolFace = Nc;
670         obj.CoefficientFriction = mu;
671         obj.ShearStress = tau;
672         obj.NormalStress = sigma;
673         obj.RatioR = r;
674         obj.ShearEnergyVolume = us;
675         obj.FrictionEnergyVolume = uf;
676         obj.FrictionAngle = beta*180/pi;
677     end
678
679     function obj = calculatePecletNumber(obj)
680         cp = polyval(obj.heatCapacity,obj.MaximumTemperatureCuttingZone);
681         k = 75.4;
682         d = 7.85*10^-3;
683         obj.PecletNumber = ((obj.CuttingVelocity/60)*obj.UnCutChipThickness)/(k
/(cp*d));
684     end
685
686     function vH = displayHeatCumulateperLine(obj)%Fix this function
687         d = zeros(size(obj.ptosLines,1),1);
688         d2 = zeros(size(obj.ptosLines,1)-1,1);
689         pp = 15*10^-3;%mm/pixel
690         for i = 1:size(obj.ptosLines,1)
691             d(i) = pp*((obj.CoordinateToolTip(1) - obj.ptosLines(i,1))^2 + ((obj
.CoordinateToolTip(2) - obj.ptosLines(i,2))^2))^(1/2);
692         end
693         for i = 1:size(obj.ptosLines,1)-1
694             d2(i) = pp*((obj.ptosLines(i+1,1) - obj.ptosLines(i,1))^2 + ((obj.
ptosLines(i+1,2) - obj.ptosLines(i,2))^2))^(1/2);
695         end
696         d2 = mean(d2)*10^-3;
697         figure
698         plot(d,obj.heatAccumulatedPerLine,'-x')
699         hold on
700         q = gradient(obj.heatAccumulatedPerLine,d2);
701         plot(d,q,'-r')
702         vH = [d obj.heatAccumulatedPerLine];
703     end
704 end
705 end

```

FOLHA DE REGISTRO DO DOCUMENTO

1. CLASSIFICAÇÃO/TIPO TC	2. DATA 22 de novembro de 2017	3. DOCUMENTO Nº DCTA/ITA/TC-031/2017	4. Nº DE PÁGINAS 50
5. TÍTULO E SUBTÍTULO: Computational method for temperatures and heat flows analysis of orthogonal cutting 1045 steel by thermal imaging			
6. AUTORA(ES): Adriana Nunes Chaves Lima			
7. INSTITUIÇÃO(ÕES)/ÓRGÃO(S) INTERNO(S)/DIVISÃO(ÕES): Instituto Tecnológico de Aeronáutica – ITA/IEM			
8. PALAVRAS-CHAVE SUGERIDAS PELA AUTORA: Manufacture; Image Processing; Matlab; Thermal Analysis; Orthogonal Cutting; Software.			
9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO: Fabricação; Processamento de Imagens; Programas; Análise Térmica; Engenharia mecânica.			
10. APRESENTAÇÃO: <input checked="" type="checkbox"/> Nacional <input type="checkbox"/> Internacional ITA, São José dos Campos. Curso de Graduação em Engenharia Mecânica. Orientador: Anderson Vicente Borille; coorientador: Thorsten Augspurger. Publicado em 2017.			
11. RESUMO: Methods for inspection and monitoring have been used each time more to guarantee the quality of processes. In the machining field there are many important parameters to assure that a process provide the designed results. The superficial finishing of a workpiece and the life of tool are some examples subjected to the direct influence of thermal energy generated in the cutting zones. Due to it, there are a lot of theoretical methods for temperature modeling along the cutting zone, but still there is a lack of tools able to allow a practical validation of these methods. Although many challenges still prevail on the suitable use of thermography, this technology makes possible the development of computational methods that allows the thermal image processing and, consequently, the heat flow and heat partition analysis afterwards. This paper comes to present a computational method developed on MATLAB, with image processing toolbox support. It makes thermal image analysis, providing results about temperature fields, inner energies, heat flows and other variables of interest that can be used on machining monitoring and studies to improve cutting parameters.			
12. GRAU DE SIGILO: <input checked="" type="checkbox"/> OSTENSIVO <input type="checkbox"/> RESERVADO <input type="checkbox"/> SECRETO			