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Emissivity calibration for temperatures measurement using thermography in the context of machining

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HIGHLIGHTS

- We built an experimental device able to record both luminance and temperature of a sample surface without oxidation.
- We used this device to extract an emissivity curve depending on temperature for the 316L.
- We used the emissivity curve to calculate temperature fields during turning.
- We found interesting temperature levels closed to the tool edge.

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ABSTRACT

This paper will present the infrared thermography principles applied to the thermal fields recording during orthogonal cutting of 316L stainless steel. This paper is divided in three parts. First, emissivity curve of 316L is extracted by warming up a sample and dividing recorded grey levels by black body ones. This first step requires the design of special equipment that allows controlling temperatures and atmosphere while recording. Next, the IR camera equipped with a microscope is integrated in a CNC lath to record grey levels while orthogonal cuttings of 316L samples. To finish, the recorded grey levels fields are then numerically post treated using homemade emissivity curve to plot the thermal gradient created during machining. All these works are important to increase the cutting analytical and numerical models accuracy especially in the thermal field prediction.

1. Introduction

1.1. Thermal aspect of cutting

It's well known that cutting of metal produces a large amount of energy, mainly dissipated as heat, as mentioned by Altintas [1]. Friction phenomenon and thermo mechanical characteristics of the work material (auto-heating) are the main sources of heat. Many experimental and analytical studies have been performed to determine the amount of load and heat applied to workpiece. Zemzemi [2] has shown the influence of friction over heat generation at the tool chip interface for a standard steel, and Valiorgue has worked with a stainless steel [3], using of dedicated tribometer. Bonnet [4] uses finite element modeling to show influence of thermal aspects over workpiece characteristics, such as residual stress. Both workpiece and tool are affected by the heat generated at the tool chip workpiece interface. The thermal contact resistance is mainly responsible of heat repartition at tool/chip and tool/workpiece interface, as shown by Courbon in Ref. [5]. For example, chipping of the tool and workpiece deformation are mainly driven by thermal aspects. Attanasio use finite element modeling in Ref. [6] to illustrate influence of heat over tool wear. Ceretti [7] try to model this heat generation at tool chip interface, in order to feed computer simulation. In case of high speed machining, or difficult to machine material, heat is always the main problem, and leads to catastrophic failure of tools [8].

Heat and temperature estimation are key points to optimized cutting process. Davies [9] exposed a historical review of thermal measurement showing that the main issue of thermocouples is that it gives only one point of measurement which is not enough to characterize the heat flux. Therefore in order to measure a thermal field which drives the thermo mechanical load and its speed, a complex setup has to be developed by using many thermocouples

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Nomenclature

h	Plank's constant, 6,626176.10^{-34} J S
k	Boltzman's Constant, 1,380662.10^{-23} J K^{-1}
c	light celerity, 2998.10^{8} m s^{-1}
$c_1 = 2\pi hc$	constant
$c_2 = h.c/k$	constant
$L_\lambda(\lambda,T,\Delta)$	value of luminance, for wavelength λ, at temperature T and direction Δ
T	temperature
$R^S_{\lambda_1-\lambda_2}$	total radiation in wavelength bandwidth between λ_1 and λ_2, for a sample S
ε	emissivity
A	area of measurement
N	ratio between the focal length and the lens diameter

like Luchesi [10]. The IR thermography is another answer to this request. It allows to measure directly, and with a high spatial and temporal resolution, all the field in the cutting zone [11,12]. Moreover, it's well known that physical phenomenon occur closed to the surface (about 0.5 mm depth), like heat affected zone (HAZ) or metallurgical changes [13].

1.2. Physics of thermography

Each material body absorbs and emits energy in the form of radiation, as Pajani noted in Refs. [11,12]. For solid bodies, thermal restlessness of atoms and electrons generate vibrations of the crystal lattice and electrons movements, which lead to photons emission (thanks to quantum mechanics).

For opaque bodies, only surface emitted photons are responsible of the solid radiation and at the microsecond scale, photons emission is a rare and unpredictable phenomenon. The measurement of this radiation can be done by thermal imaging, or pyrometric device. Herve [14] uses a two-color pyrometer to determine surface temperature of sample, after emissivity calibration with a HgCdTe nitrogen cooled infrared detector. Other surface thermal characteristics (thermal diffusivity and conductivity) can be obtained by thermal imaging, like Boué in Refs. [15], using the same kind of thermal camera (InSb sensor). Arriola [16] uses a specially infrared camera coupled with a standard high speed sensor developed in the NIST to record temperature during cutting. In every case, the knowing of emissivity is the key to reliable measure of temperature.

For the understanding of the emissivity parameter, physicists define an ideal body capable to absorb all the incident radiation called black body. According to the energy conservation principle, this black body is also a perfect transmitter for the entire spectral domain, all the directions only depends on temperature. The luminance of a black body and temperature are linked together by the Plank's law given with Equation (1).

$$L^0_\lambda = \frac{c_1\lambda^{-5}}{\pi\left[\left(exp\frac{c_2}{\lambda T}\right)-1\right]} \quad (1)$$

To determine the monochromatic luminance of real bodies, an emission factor called emissivity (ε) is defined as the ratio between the real monochromatic luminance and the black body one (Equation (2)). It depends on the wavelength, the temperature, the emission direction, the material and the surface characteristics. The emissivity value is between 0 and 1.

$$\varepsilon = \frac{L_\lambda(\lambda,T,\Delta)}{L^0_\lambda(\lambda,T)} \quad (2)$$

Boué explains in Ref. [15] that the lack of precision on emissivity value leads to a wrong temperature estimation. The bandwidth selection is also important, as noted by Meca Meca [17], because in range [3–5 μm], the atmosphere is highly transparent to radiation, which enables precise measurements even at greater distances.

Thermography consists in recording radiations emitted in the infrared domain. In this domain, luminance is the highest, as shown on Fig. 1, ambient air is transparent and radiations are not submitted to reflexion or diffraction phenomena.

2. Emissivity determination

2.1. Principle

Equation (3) expresses the voltage recorded by the detector depending on luminance L_λ, a constant K. For black body and sample acquisition operations, the microscope mounted on the camera and the focal length remains identical so the second term of the equation remains constant for both calibration and measurement. V is called the grey level.

$$V = L_\lambda \times \frac{K\times A}{N^2} \quad (3)$$

With this set up it is possible to record V depending on temperature for the black body ($V^{BB}(T)$) and the sample ($V^S(T)$). While the experimental set up remains the same for calibration and measurement, it becomes possible to determine emissivity by dividing $V^S(T)$ by $V^{BB}(T)$ (Equation (4)).

$$\frac{V^S(T)}{V^{BB}(T)} = \frac{L^S_\lambda\times\frac{K\times A}{N^2}}{L^{BB}_\lambda\times\frac{K\times A}{N^2}} = \frac{L^S_\lambda(T)}{L^{BB}_\lambda(T)} = \varepsilon(T) \quad (4)$$

2.2. Experimental set up

A dedicated experimental device has been set up to obtain results as precisely as possible by taking into account all the main parameters having an influence on the material emissivity (roughness, angle, oxidation,…). An oven which heats the material sample (cylinder with ground face), a thermocouple which records temperatures on the measured face of the sample (supposed homogenous) and a protective tube which ensures a neutral atmosphere (nitrogen) and absorbs parasite radiations (Fig. 2). During all these experiments a FLIR camera records the luminance levels emitted by the sample for a given temperature value. By this way it is possible to link the luminance level and the temperature of the face. The surfaces of the samples are ground to control the surface roughness. Other researchers use also a calibration step in order to fine tune the camera for the specific measurement ([14,16]).

Fig. 3 presents the grey levels depending on temperature and recording for a black body (ref) which shows that the sensor do not have a linear response depending on temperature and that's why the grey level/temperature curve is not a straight line.

The following curve (Fig. 4) provides the grey levels depending on temperature for the 316L ground surface. Due to the experimental set up, the surface temperature cannot exceed 550 °C. It is related to the oven capacity and material conductivity (very low for austenitic steels). To enlarge the temperature range, grey levels have been linearly extrapolated up to 650° (red points), because

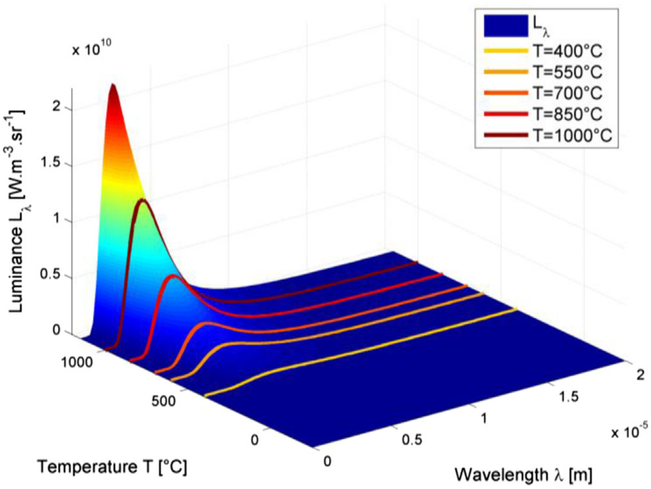

Fig. 1. Luminance as a function of temperature and wavelength.

over 500 °C, grey level can be assumed to be proportional to temperature.

As it can be seen, the temperature levels for which the grey levels were recorded cannot exceed 820° for the black body and 650 °C for the workpiece. By the way, these maximum values are sufficient enough if only the HAZ is considered in the workpiece which is the main issue of our works. In fact, temperature can reach higher values in the chip [5] but it is not possible to measure it with the presented infrared method and the study focus on workpiece temperature.

The following curves (Fig. 5) present the 316L emissivity extracted curve with our experimental device, for a ground surface and luminance acquisition made perpendicularly to the emitting surface. After each test the measured surface is controlled visually to detect any traces of oxidation. This phenomena can only appear in a gente manner because of the constant nitrogen flow in the protective tube. Finally, by working only on grey levels, and the same optical devices, the emissivity curve is not dependent on this device.

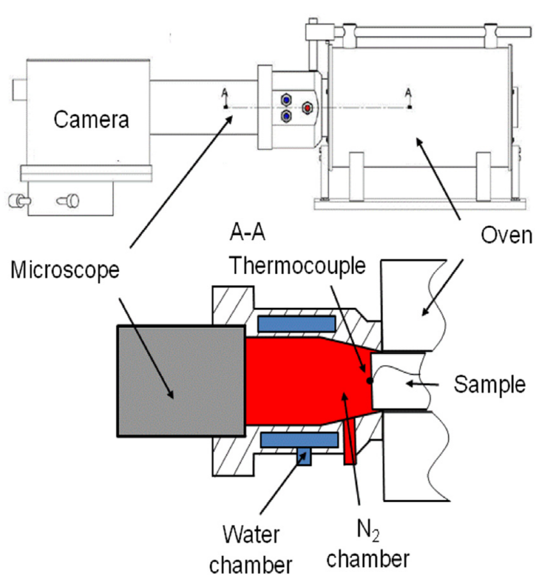

Fig. 2. Emissivity calibration system.

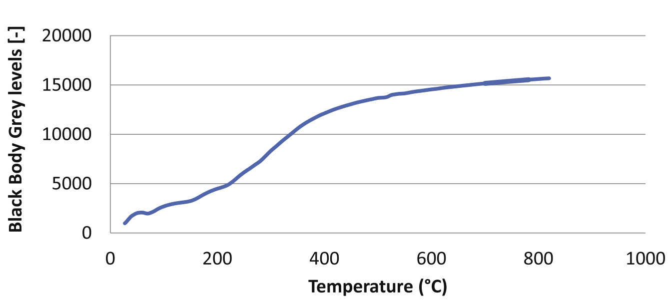

Fig. 3. Black body grey level depending on temperature.

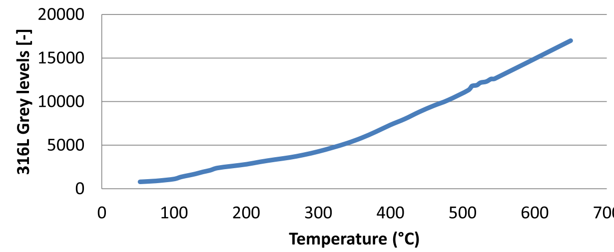

Fig. 4. 316L sample grey level depending on temperature.

2.3. Temperatures measurement method

Infrared thermography gives reliable recordings with much more accurate spatial and temporal resolutions than thermocouples commonly used in the case of machining processes. However, some specific parameters have to be defined such as, integration time, and emissivity laws. It is possible to determine real temperatures in the workpiece by using the Planck's law (Equation (1)) in the black body case. It has also been chosen a camera which uses a wavelength bandwidth (3.4 μm–5 μm) where luminance is maximized for recorded temperatures corresponding to the ones obtained during machining (Fig. 6). For this wavelength, Luchesi [10] explains that the uncertainty of temperature is about 10 K for a true value of 850 K. Meca Meca shows in Ref. [17] that this bandwidth is transparent for air. This type of sensor is widely used in case of temperature measurement in machining (Davies [9], Abukhshim [8]). The IR camera is a FLIR System device, with an InSb sensor. The resolution is 320 by 256 pixels. Germanium lenses are used in order to protect glass optics form excessive heating during temperature recordings.

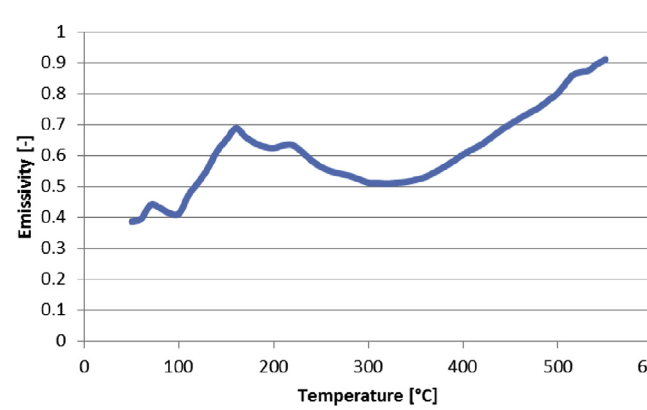

Fig. 5. 316L emissivity curve depending on temperature. For a ground surface. Without oxidation. Perpendicularly to the surface. Depending on temperature.

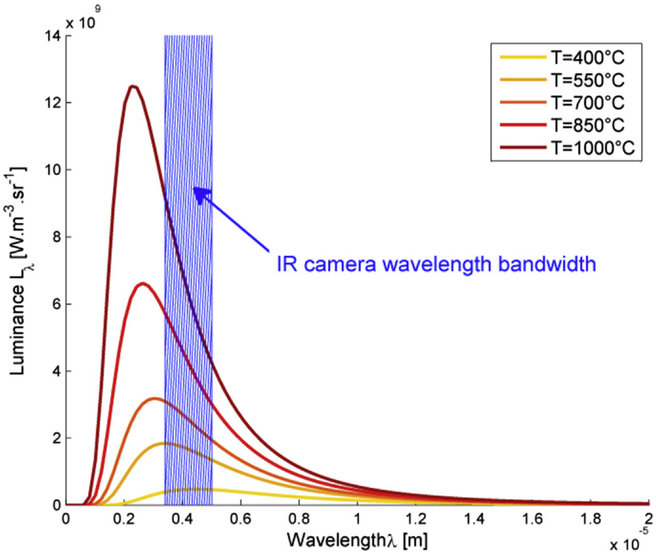

Fig. 6. Camera bandwidth.

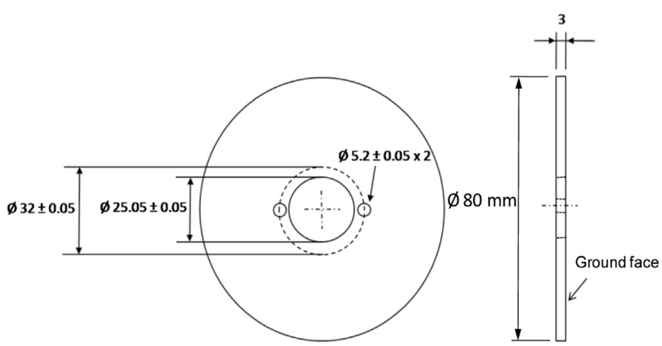

Fig. 7. 316L Discs.

In this range, the luminance can be defined by the following Equation (5).

$$R^0_{3.4-5\ \mu\text{m}} = \int_{3.4\ \mu\text{m}}^{5\ \mu\text{m}} \frac{c_1 \lambda^{-5}}{\pi\left[\left(exp\,\frac{c_2}{\lambda T}\right) - 1\right]} d\lambda \tag{5}$$

Equation (5) which is the unit surface area emitted radiation corresponding to the camera wavelength bandwidth is difficult to solve directly. To use it, it has been proposed the 1D gauss numerical integration method to obtain the black body luminance. Finally, from the black body luminance in the wavelength bandwidth and by knowing the material emissivity, it is possible to determine the workpiece temperature. As one can see, measuring a precise thermal filed is driven by the fine knowing of material emissivity, thermal laws, and a dedicated IR camera. The temperature measurement procedure is as follows:

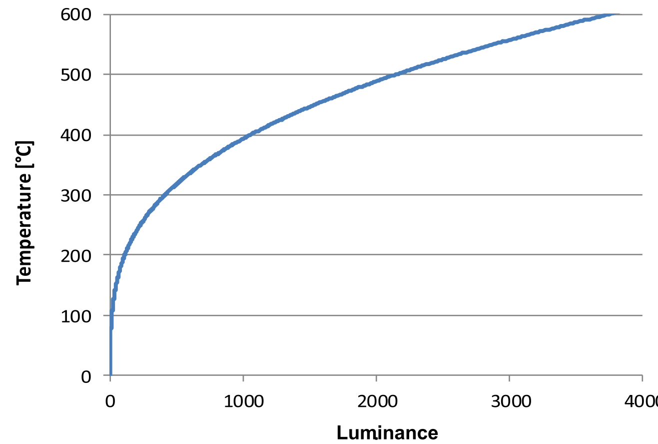

Fig. 9. Luminance for a black body in a range of 3–5 μm (W m^{-2} sr^{-1}).

- Radiation recording for the 3.4–5 μm wavelength bandwidth,
- Numerical integration
- Black body temperature determination
- Real temperature calculation using emissivity

Infrared camera records luminance levels emitted by the workpiece during machining. With this measurement it is possible to obtain temperatures by the means of the material emissivity. First luminances are recorded and then, by the means of emissivity calibration and MATLAB® integration procedure, temperatures fields can be obtained.

3. Temperature fields in turning

3.1. Experimental set up

The temperature measurements are made using orthogonal cutting test. This device is developed on a Transmab T450 CNC

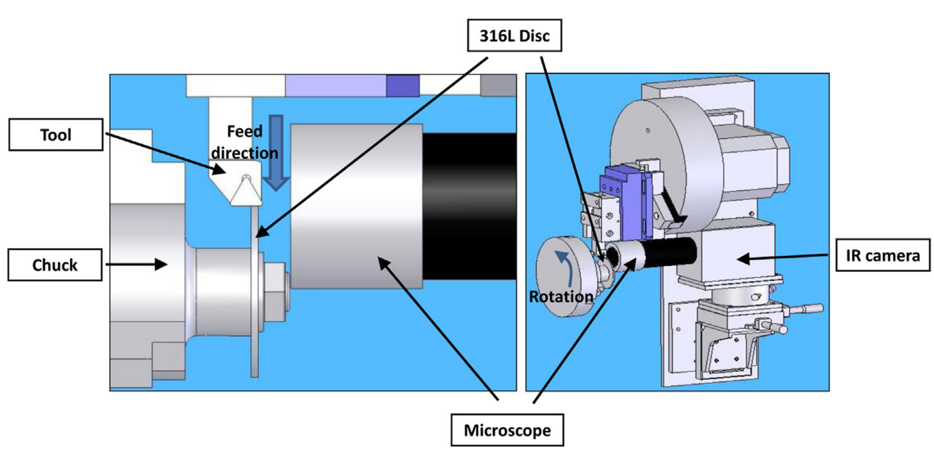

Fig. 8. Experimental set up.

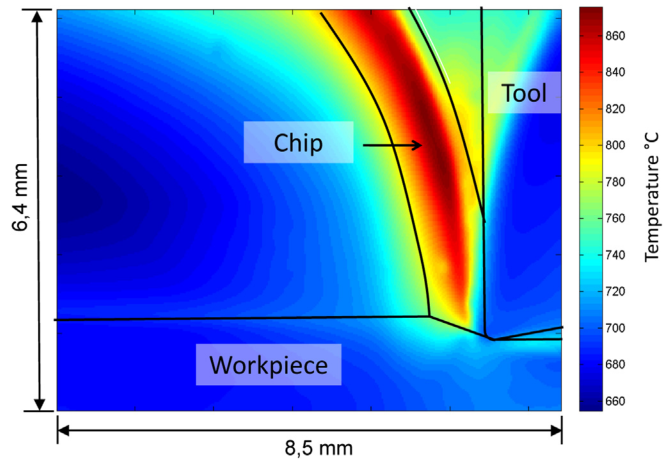

Fig. 10. Temperature in the chip (Vc 120 m min^{-1}, *f* 0.1 mm tr^{-1}).

lathe. A 3 mm thick disc of AISI 316L presented in Fig. 7 is mounted in the chuck. TPKN 1604 inserts and H13A carbide coated with TiN are used. The tool holder is mounted on a three components Kistler dynamometer. The IR camera is set up so as to have the axis of the camera perpendicular to the disc. Series of germanium lens is used to obtain a 8.5 by 6.4 mm windows, centered on the cutting edge of the tool, for a 320 by 240 pixels resolution. In this configuration, the IR camera follows the plunging movement of the turret during machining, so the video recorded is almost on steady state. The feed movement between the tool and the workpiece is compensating by the turret displacement and all the geometrical values remain unchanged. All the devices are illustrated on Fig. 8.

For this configuration, the optical set up is not the same as the one used to calibrate the emissivity. The series of lens used to magnify the cutting scene and the protecting bushing necessitate the use of the emissivity curve and Planck's law integration to obtain thermal fields (Fig. 9).

3.2. Planck's law integration

For the treatment of the experimental values, an expression of the temperature in function of the Luminance is required. Then as an analytical integration of the Planck's law does not exist, a numerical approximation is performed. For that purpose, since the luminance curb is strictly monotonic in the range of the infrared camera used in experiments, a trapezoidal method with unit spacing is used to integrate from the wavelength of 3.4–5 μm. A small integration step of 0.01 μm is chosen to obtain the final relation of the temperature in relation with the luminance of a black body as shown in Fig. 10.

3.3. Temperature in the chip

The first attempt of temperature measurements were made onto the whole cutting scene. Fig. 10 presents the temperatures isovalues.

In this case it appears firstly that the chip temperature value exceeds the maximum reached during the calibration. Secondly, the chip surface is really far from the one used to calibrate the emissivity curve. Finally, the insert used for this operation is a carbide one and its emitting properties have not been integrated. As a conclusion, temperature recordings for the whole scene do not seem to be relevant and that is why a second attempt was performed to estimate only the thermal fields in the workpiece under the cutting scene.

3.4. Temperature in workpiece

A second series of tests was performed where the chip formation zone and the tool were hidden. This unable to record temperatures fields under the tool, in the workpiece (Fig. 11).

This maximum temperature levels (around 500 °C) are in good agreements with the one found with hybrid method concerning only the workpiece [3]. The tests underline the ability of infrared thermography to provide thermal fields with an accurate spatial resolution.

3.5. Discussion

The first part of this paper, corresponding to the emissivity calibration depending on temperature is important because this can be used for a lot of other applications. This has been performed with a new experimental set up, close to the conditions that can be found during industrial tests (surface aspect, distance between camera and workpiece,...). Grey levels were acquired with exactly the same optical configuration for both the black body and the 316L sample and the ratio between these two values provides an accurate emissivity curve because no major assumption were made during the experimental procedure.

In the second part, the emissivity curve of 316L was used to record thermal fields because the configuration has changed. This operation allows testing the first results and, for the thermal fields calculation, a sensitivity study concerning emissivity has been performed. For a variation of 20 percent, temperatures increase or decrease of respectively between −13% and +7% in the range of temperatures met. The emissivity variation shifts the temperature field values and do not modify the temperature gradients. The second important point for measurements precision is the choice of the observed zone. High temperatures area can dazzle the camera and hide lower temperature regions. This is the major limitation of this procedure and thermal gradients and heat flows can difficultly be extracted.

Simulations need heat flux and thermal properties to reproduce the thermal phenomenon and predict the temperature fields. Recordings only provide temperature levels and currently these temperatures measurements cannot be considered as input data for analytical or numerical machining models but they can reinforce them by comparing experimental and numerical results.

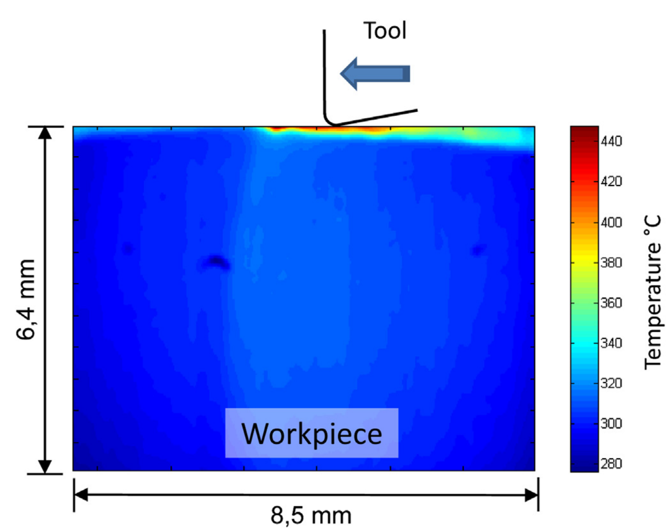

Fig. 11. Temperature in the workpiece. The tool and chips are physically masked.

4. Conclusion

This paper presents the hypothesis used for tempera ture measurements using infrared thermography in the context of machining. Based on these physical laws an emissivity calibration device has been set up. This equipment allows to record luminances while a sample is heated so as to extract the emissivity curve depending on temperatures, for a ground surface, and filmed perpendicularly to its surface. With this emissivity curve it has been possible to obtain temperatures fields useful to reinforce analytical and numerical models of turning. Future works will also permit the characterization of the heat flows generated by these two kinds of machining operations and applied to the workpieces by recording temperature levels layers by layers so has to overcome dazzling.

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