POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Characterization and compensation of the thermal expansion of Al5754 during the laser cutting process

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

AUTHOR: Andrea Daloiso

ADVISOR: Dr. Leonardo Caprio

CO-ADVISOR: Matteo Busatto

ACADEMIC YEAR: 2021-2022

1. Introduction

Today, laser cutting of sheet metal and tubes has become a key production technology for the industrial sector due to its numerous advantages such as reliability, efficiency and high productivity.
Thanks to the recent developments in fibre laser cutting, it is now possible to cut also highly reflective materials such as aluminium, which has become an extremely widespread material due to its very interesting mechanical characteristics and physical properties.
Despite the many advances that have been made, such operations are by no means free of problems that affect the quality of the cut.
While optimal cutting parameters have been sought for the boundary conditions that can be controlled, there are numerous factors that cannot be controlled by the user that often led to a drop in cut quality. One of these is the increase in the temperature of the workpiece after repeated cuts, which is inevitable and not well-controllable.
In this thesis work, to understand the effects of the increase in temperature on the quality of aluminium laser cutting, a thermal expansion model was introduced and analysed.
After that, any problems that may have arisen were corrected, by adjusting the cutting parameters and developing a compensation model to solve the dimensional problem.

2. State of the art

Aluminium (Al), occurs in great abundance, being the second most plentiful element in the earth's crust: its compounds in fact form 8% of the latter.
The properties and peculiarities of aluminium well explain why this metal production and usage is increasing so much over the years.
The capability of laser cutting technology mainly depends on the optical and thermal properties

rather than the mechanical properties of the material to be cut. [1]
Aluminium (Al) and its alloys are considered difficult-to-cut materials with laser cutting process [2] because it is affected by:

- High reflectivity that requires higher laser power and causes problems of back-reflection;
- High thermal conductivity that produces a larger heat-affected zone (HAZ);
- High viscosity of the molten material.

The proper selection of process parameters plays a crucial role to gain the required cut quality in such materials. For that reason, the effects of the different process parameters on the cutting quality were investigated for the detection of the optimal cutting parameters, which obviously depend on various conditions, one of the most important of which is the thickness of the material to be cut, as this leads to the modification of various parameters such as focal position, power, cutting speed or Stand Off Distance (SOD).
Different standards define possible imperfections, defects, and dimensional tolerances and impose survey criteria to quantify the quality of laser cutting.
Defining imperfection as any irregularity with respect to the specified shape of the cut and defect as an imperfection that cannot be accepted.
The main effects analyzed in this thesis work have been the roughness of the cut surface, the dross formations on the bottom surface of the pieces (Figure 1), and above all the thermal expansion phenomenon that led to dimensional inaccuracies.

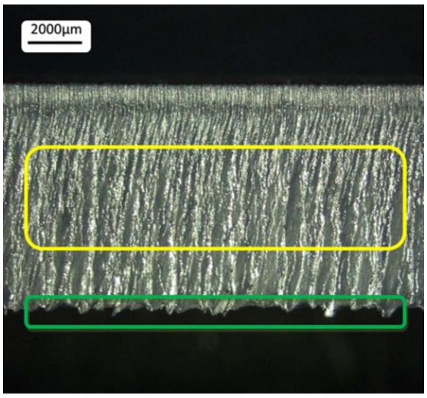

Figure 1: Example of striation (Yellow) and burr formation (Green) on an aluminium sample cut with melt and blow cutting

Up to 75 % of the overall geometrical errors of machined workpieces can be induced by the effects of temperatures [3].
For this reason, the thermal stability of the machine tool and the processed material is of critical importance.
The dimensional error parameters are calculated from the difference between nominal and measured length since a change in temperature from the reference one causes a change in space and hence the need to compensate for this geometric error.

3. Aims of the work

The aim of this thesis work was to investigate the deterioration in the cutting quality of aluminium Al 5753 due to heat accumulation and cutting at high temperatures, carried out for different thicknesses of the aluminium sheet, and identify a possible critical temperature that would lead to a deterioration no longer acceptable.
It was also of considerable importance to experimentally analyse the thermal expansion to which the sheet metal was subjected at various temperatures in order to compare it to theoretical models of linear thermal expansion and to develop a strategy to eliminate or mitigate this problem.
A diagram of the development of this work is shown in Figure 2.

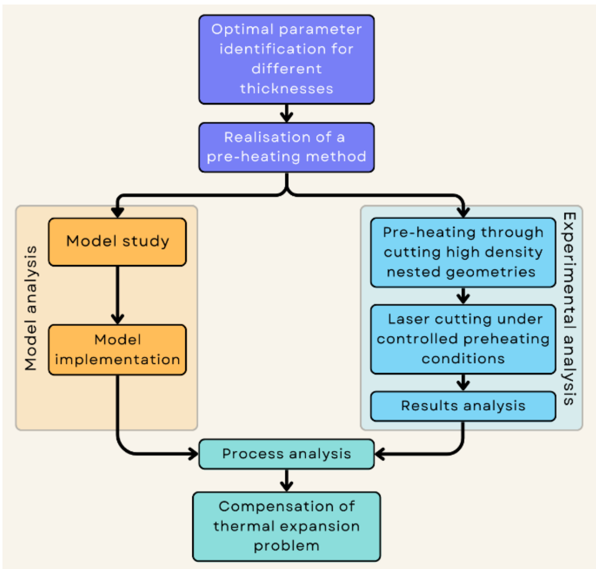

Figure 2: Thesis work scheme

4. Model

Aluminium is a metallic material that has one of the highest thermal expansions among metals. The coefficient of linear thermal expansion of aluminium is approximately 23.1x10^-6 /°C, which means that for every degree Celsius of temperature increase, aluminium will expand by approximately 23.1 μm per meter in length.
It is possible to consider three different types of thermal expansion [4], depending on whether the one-dimensional (linear expansion), two-dimensional (superficial expansion), or three-dimensional case (volumetric expansion) is to be analysed.
A difference from the theoretical model is that in the linear expansion equations, we consider an additional term that considerably altered the dimensions of our final sample after cutting, namely the laser cutting kerf, which reduced the size of the sample and had to be appropriately compensated in order to obtain the nominal sample size even at room temperature.
The total expansion of our sample will therefore be the sum of two different terms:

$$e_{TOT} = e_{Corr} + e_{\Delta T} \qquad (4.1)$$

where the value ε_{TOT} represents the total relative expansion.
e_{Corr} represents, the dimensional value that take into account the cutting kerf, which must be compensated for through the use of the tool offset corrector, directly imposed on the machine, given by:

$$e_{Corr} = \frac{2 * \Delta_{Corr}}{L_o} = \frac{2 * (Corr_1 - Corr_0)}{L_o} \qquad (4.2)$$

Where ΔCorr is the increase in the tool offset corrector value due to the increase of temperature, $Corr_0$ is the tool offset corrector value at ambient temperature, and $Corr_1$ is the new tool offset corrector value at higher temperature to compensate for the expansion problem.

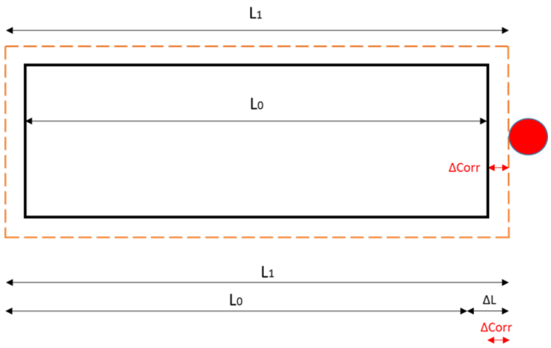

Figure 3: ΔL and ΔCorr comparison to compensate expansion problem

Finally, the $\varepsilon_{\Delta T}$ represents the expansion due to thermal phenomena and so due to the increase or decrease in temperature values:

$$e_{\Delta T} = \frac{\Delta L_{\Delta T}}{L_o} = \alpha \Delta T \qquad (4.3)$$

The length of the expanded sample after temperature increase will therefore be given by:

$$e_{TOT} = \frac{L_x - L_o}{L_o} = \frac{2 * \Delta_{Corr}}{L_o} + \alpha \Delta T \qquad (4.4)$$

we can finally go on to calculate the tool correction value that we will need for the final task of compensating for this error:

$$Corr_1 = Corr_0 + \frac{L_x - L_o - L_o * \alpha \Delta T}{2} \qquad (4.5)$$

fundamental equation that will lead us to the final compensation we have set ourselves and which must be analysed and confirmed experimentally.

5. Experimental setup

In this section, all the measurement and analysis instrumentations used in the conduction of this thesis work are presented.

5.1. Temperature measurement equipment

The primary objective of this work is to bring the aluminium to high temperatures before cutting it and checking its quality, so we first need to analyze what are the instruments and methods by which

the measurement of the plate temperature was carried out.
For this purpose, two instruments, based on two different measurement methodologies, were used: one based on contact measurement method and the other on remote measurement.
The first one involved the use of K-type thermocouples, that can be seen in Figure 4.
In general, a thermocouple consists of two wires of different metals. When the two filaments are joined at one end and the junction is heated, a current is generated within the two filaments that induces a voltage between the free ends of the wires: by measuring the voltage, the temperature of the junction can be determined.

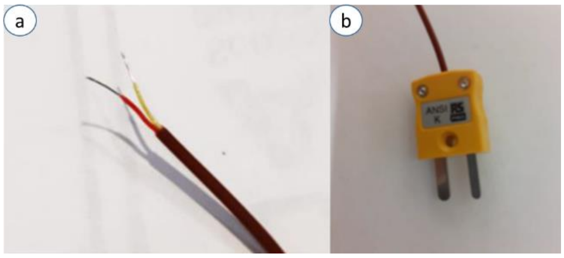

Figure 4: Wire junction to be welded (a) - Thermocouple K-type connector (b)

The second method, instead, involved the use of an infrared thermographic equipment, where the thermal image indicates the distribution of temperature on the surface of an object. With a thermal imaging camera, it is therefore not possible to make an analysis inside or through the object.
The infrared thermography equipment at our disposal was the FLIR X6900sc camera model (Figure 5).

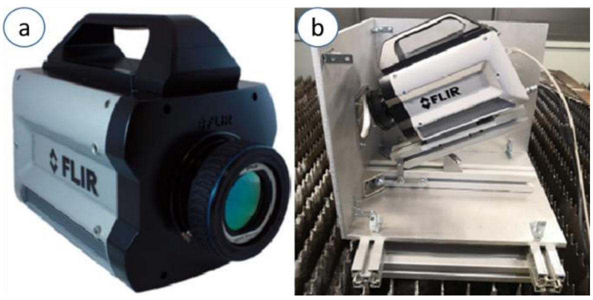

Figure 5: X6900sc thermal camera model (a) – Thermal image camera with support base (b)

5.2 LC5 Laser cutting system

The laser cutting machine used in this thesis project is a customized version of the LC5 machine (LC5, Adige-SYS S.p.A., BLMGroup, based in Levico Terme (TN), Italy, Figure 6).
The LC5 is available with a fiber laser source of power up to 6 kW, working with a 1.070 µm wavelength. (YLS-6000-CUT, IPG Photonics Coorp., Oxford, Massachussets).
A high-pressure nitrogen inert gas was used to perform the melt and blow method for aluminium cutting.

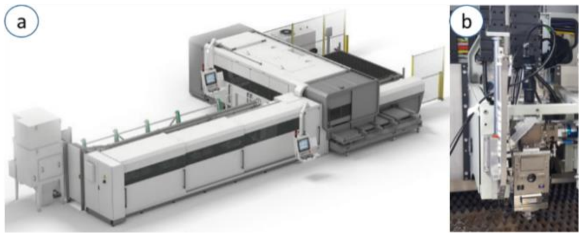

Figure 6: Combined LC5 laser cutting machine (a) – HPSSL, Precitec Laser cutting head (b)

5.3 Roughness measurement procedure

Roughness measurements are performed as explained in ISO 9013:2017, where the roughness value, Rz5, is one of the parameters that is able to define the quality of the cut edge.
The measurements are performed at three different heights of the samples as can be seen in Figure 7:

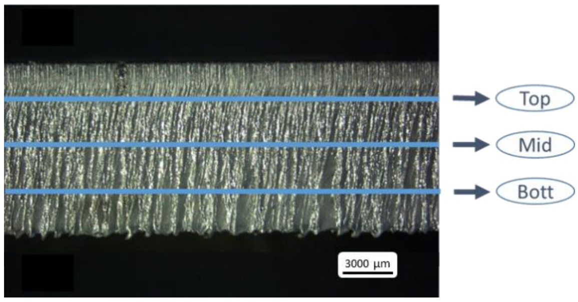

Figure 7: Three different roughness acquisition height

Roughness measurements are performed using a linear profilometer (Perthometer Concept PCMESS7024357, Mahr GmbH, Esslingen, Germany) shown in Figure 8.

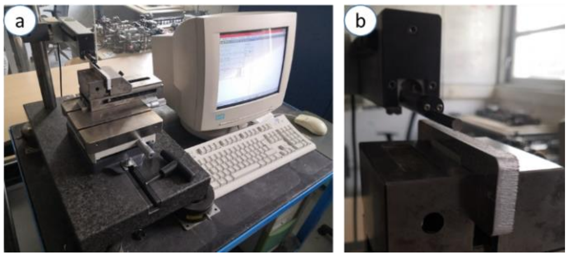

Figure 8: Mahr Perthometer PGK (a) – Contact stylus with 5 µm tip MFW-250 (b)

5.4 Dross measurement procedure

According to ISO 13705:2000, dross entities are calculated as the entire length exiting the bottom edge of the sample.
The procedure starts with the acquisition of high-contrast images of the side surfaces that needs to be analyzed. After that, the pictures are analyzed through a specific MATLAB code, that binarize the images and extracts the upper and lower contours and finally calculates the mean value and the standard deviation of the dross attachment (see Figure 9).

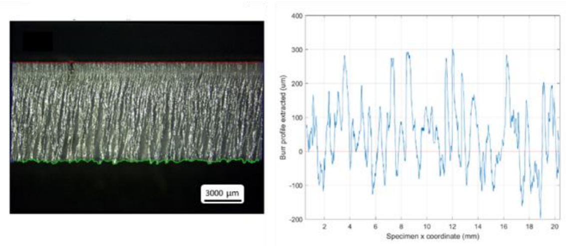

Figure 9: Dross attachment elaborated through MATLAB Code

5.5 Dimensional measurements

For the dimensional analysis an optical microscope (Mitutoyo Quick Vision PRO ELF QV-202) was used, shown in Figure 10.

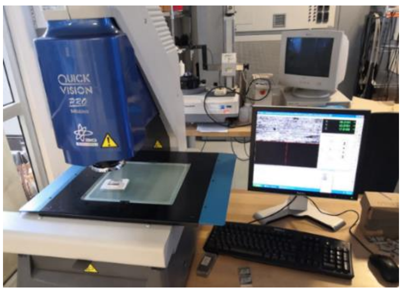

Figure 10: Optical microscope Mitutoyo Quick Vision PRO ELF QV-202

Specimens dimensional measurements were performed with the optical microscope.
Several measurements were taken along both the X and Y axis.
These were performed by placing the samples on the measurement table, defining the reference system and checking the X Y and Z values of one side. We then going to vary only one parameter (X in case you want to measure the length along the x-direction), maintaining constant the other two, until the final sample length was measured (the procedure is briefly shown in Figure 11).

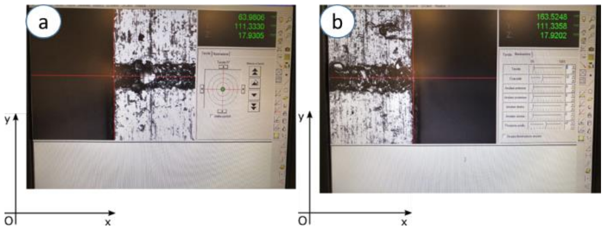

Figure 11: Dimensional measurement procedure. (First measurement (a) – Second measurement (b)

6. Hardware for experiment under controlled heating conditions

In this thesis work, cartridge heaters by Elenorm S.r.l. were used in combination with the LC 3500 Dual temperature control unit for controlled heating conditions.
The diameter of these cartridge resistors was 10 mm, the length 135 mm, these developed a power of 800 W and were supplied with 230 V direct current.
Starting from the available resistors, a device (Figure 12) was created for the purpose, an allocation base with cylindrical-shaped holes for the insertion of the cartridge resistor, intended to heat up the aluminium workpiece material in a homogeneous and controlled way.

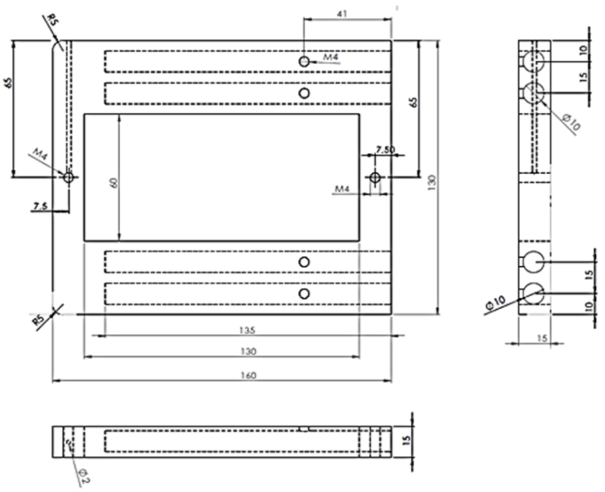

Figure 12: Design of the Cartridge electric resistance allocation base

This device was equipped with an M4 screw system both to secure the electrical resistors inside it and prevent them from escaping during the various operations and to be able to easily mount and dismount an additional aluminium plate of appropriate size on it so as to perform the cutting after heating.
In Figure 13 it can be seen the 3D model developed, and a two-millimeter-thick aluminium base of considerably larger size than the heating base itself was also included, this was done to ensure vibration stability and to avoid movement due to high gas pressures during cutting.

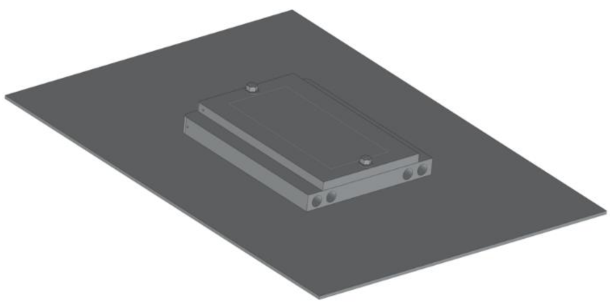

Figure 13: SolidWorks 3D model of the allocation base set-up

A two-millimeter-diameter side hole was added to provide access for a thermocouple that was responsible for real-time monitoring of the temperature of the base and the part itself.
In Figure 14 the final setup layout is shown, the wires sticking out from the base, show the position of the cartridge resistors properly inserted inside it, the thermocouple positioned inside the side hole, and finally some counterweights to prevent bending of the aluminium foil underneath due to high operating temperatures and any residual stresses within it.

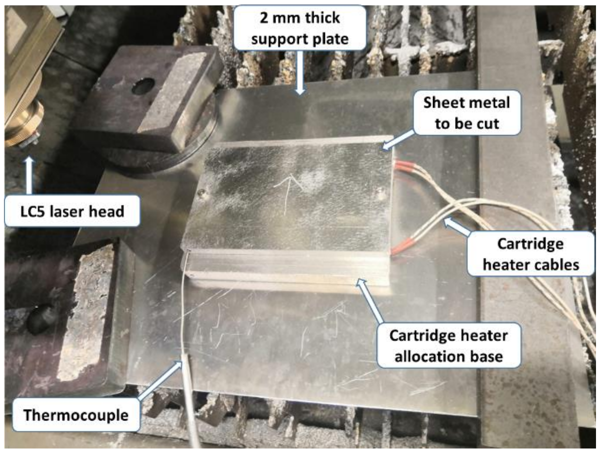

Figure 14: Final layout set-up

7. Characterizing part quality after the laser cutting under controlled preheating conditions

The experimental set-up used for heating the aluminium before cutting using cartridge heating elements, and so under controlled preheating conditions, was defined in Section 6.
Through this method, an homogenous distribution of the heat along the entire sample volume has been reached.
In addition, it gives us the possibility to control the sample temperatures during heating and, at the same time, stabilize it on the wanted values.
In the design of experiment, the optimized cutting parameters were therefore set as fixed parameters, while as a variable parameter, in addition to the thickness under analysis, the temperature was varied from 25°C up to 250°C with intervals of 75°C each (25-100-175-250°C).

7.1 Results

The DOEs were then analyzed checking the results for the different preheating method used and for the three different thicknesses analyzed (2-5-8 mm). Three types of defects were analyzed:

- Profile roughness
- Burr attachment

- Dimensional analysis.

7.1.1 Profile roughness

ANOVA analysis was done to check the influence of the variable parameters on the roughness value Rz and the measurements were performed as explained in Section 5.3.
As expected, Rz values on the top measurement are lower than on the other two measurements because of the initially laminar flow.
For all the temperatures analyzed, there was no downgrade in the quality of the cut from a roughness point of view, and no trend of increasing or decreasing roughness with increasing temperature.
In Figure 15 the individual value plot of the Rz values for all the three locations (top, middle, bottom) superimposed, to better visualize the obtained results.

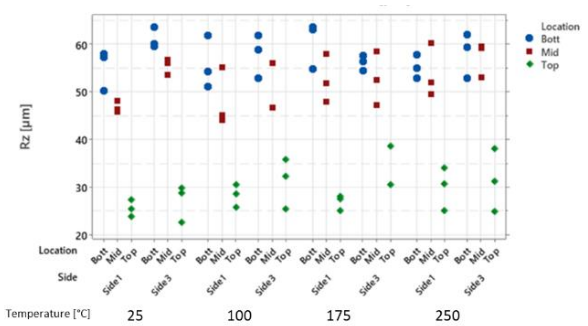

Figure 15: Individual value plot of Rz for top, middle and bottom measurements, superimposed

7.1.2 Burr attachment

The study of burr formation was then performed, using the high-quality images and a specific MATLAB code as explained in Section 5.4.
The mean and standard deviation values of the burr attachment present on the bottom surface of the specimens were therefore analyzed for the different initial temperature values.
Again, no increase or decrease in the average burr attachment values was observed. It is clear by means of controlled preheating using electric resistors, that the burr value remains completely unchanged as the temperature varies, without therefore showing any deterioration in the quality of the cut.
In Figure 16 an example of the mean burr variation as the temperature changes, for the case of the specimens of 8 mm thickness, where we can see that there are no significant variations.

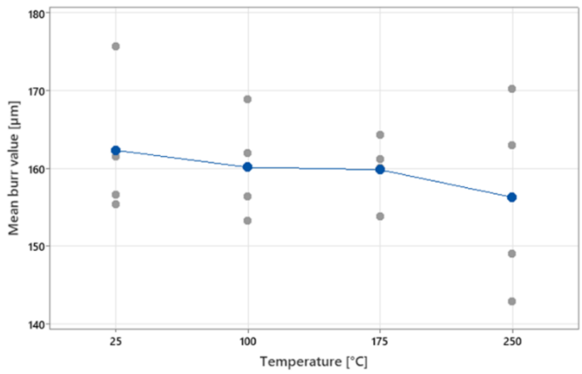

Figure 16: Individual Value Plot of Mean burr value [μm] – 8 mm thickness

7.1.3 Dimensional analysis

We then analyzed and compared the dimensional accuracy of the final part, and it is here that we notice the most significant result.
In fact, in the case of pre-heating through different methods (not described), what emerged was an anomalous behavior, with respect to the theory of the expansion of solids with increasing temperature, due to the not-homogeneous heating of the aluminium plate.
The pre-heating method through cartridge heater allocation base used, was in fact intended to solve some of the problems arising from other method, guaranteeing homogeneous heating of the entire piece, and allowing better analysis of the cut samples.
What emerged this time was a behavior that was much more in keeping with the prediction of the theoretical model. In fact, not only was the rolling direction found to be completely irrelevant in the dimensional calculation at all the temperatures analyzed, demonstrating that this was not responsible for the previous anomalous behavior, but also that the expansion of the piece on heating in both directions under analysis was obtained, with an expansion that amply respected the theoretical thermal expansion coefficient of the material.
As can be seen in the Figure 17, the samples experienced a linear reduction in size as the temperature increased.

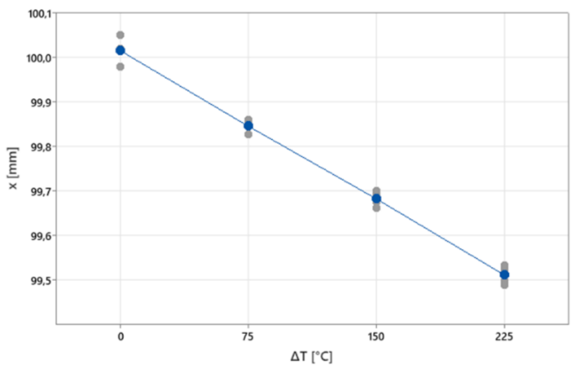

Figure 17: Length of the samples [mm] in X direction for the different temperatures analyzed – 8 mm thickness

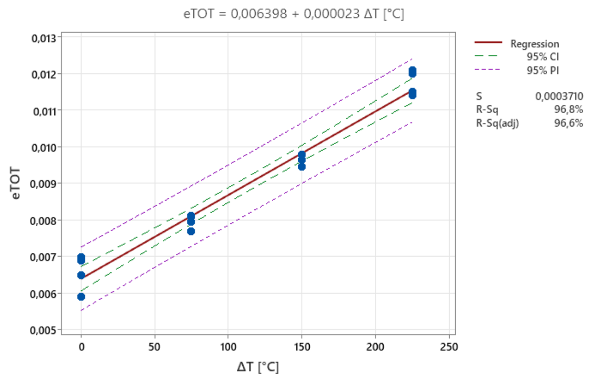

Figure 18: Regression analysis of e_{TOT} versus the variation of temperature ΔT [°C]

Looking also at the regression analysis in Figure 18, It is immediately evident that there is a constant term, which is also significant in the regression analysis.
This term is fundamental for the calculation of the tool corrector at room temperature ($Corr_o$, $\Delta T = 0$), i.e. when the $e_{\Delta T}$ term in the Equation (4.1) is zero, and the dimensional error calculated on the e_{TOT} is to be attributed exclusively to the cutting kerf width.
Considering in fact the expression of the e_{corr} in the Equation (4.2), we can easily calculate the value of the tool offset corrector at ambient temperature, $Corr_o$, rearranging that equation and using the Equation (8.1).

$$\mathrm{Corr_o} = \frac{\mathrm{L_o} * \mathrm{e_{Corr}}}{2} \tag{8.1}$$

What is also evident, is that we find a value of the angular coefficient of the regression line of approximately 22×10^{-6}. The angular coefficient of the regression model is the theoretical coefficient of linear expansion of the material under examination, where we note an extreme correspondence between the experimental values obtained and the theoretical value at all the thicknesses analyzed.

8. Compensating part thermal expansion via a predictive model

Having thus obtained a predictable and well-studied behavior thanks to the realization of the pre-heating method using cartridge heating elements, we also had the possibility of studying and realizing a compensation solution to this problem.
We devised a system that exploited the use of the tool corrector (a system already present in the cutting machine to compensate for the cutting kerf width), progressively modifying it, respecting the model obtained through experimentation and thus considering the material's thermal expansion coefficient and the temperatures analyzed, obtaining excellent results with perfect compensation for the dimensional problem previously encountered.
The value of this corrector was therefore changed, as the temperature varied, following the regression model previously analyzed in Section 4, and the data of the tool corrector values are shown in the Table 1.

Tool offset correction [mm]				
Thickness [mm]	ΔT [°C]			
	0°C	**75°C**	**150°C**	**225°C**
2	0.35	0.43	0.51	0.59
5	0.2	0.27	0.35	0.43
8	0.32	0.4	0.49	0.57

Table 1: Tool Offset Correction at different temperatures

In Figure 19 we can observe how the tool offset correction perfectly balance the thermal expansion of the part, maintaining constant the dimension of the samples for all the different temperature analyzed.

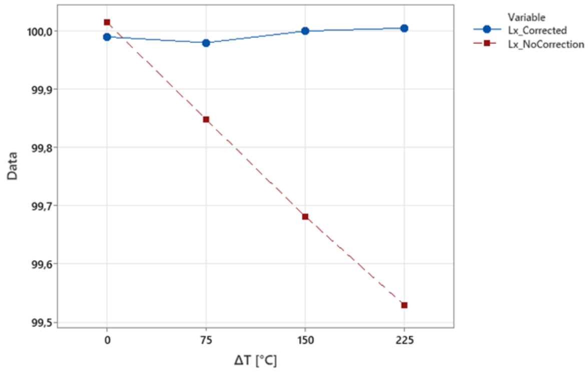

Figure 19: Length of the samples comparison with and without the use of the corrector for the compensation

9. Conclusions

In the present investigation, we have analyzed the behavior of aluminum Al5754 in response to laser cutting carried out after an increase in temperature, analyzing its quality and dimensional correctness and finding a compensating solution for the last problem.
Therefore, thanks to the realization of a reliable, repeatable pre-heating method that guarantees homogeneous heating, it would be interesting to study in the future, if for thicknesses greater than those examined in this work, a predictable behavior that respects the thermal expansion model can be maintained, as well as the possibility of studying the quality of cutting and expansion not only at higher temperatures but also for extremely different materials.
Lastly, the compensation method used to solve the dimensional problem was intended to lay the foundations for an implementation in the laser cutting machine, with the possibility of obtaining a modification of this value in the future thanks to appropriate control and real-time monitoring of the temperature of the various zones of the part to be cut, so that, where it is not convenient or not possible to intervene by modifying the cutting path or by using coolants, it is possible to obtain a final part of exact dimensions in any case.

10. Bibliography

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