CAPACITATION OF FLEXIBLES FIXTURES FOR ITS USE IN HIGH QUALITY MACHINING PROCESSES: AN APPLICATION CASE OF THE INDUSTRY 4.0 PARADIGM

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CAPACITACIÓN DE UTILLAJES FLEXIBLES PARA SU USO EN PROCESOS DE MECANIZADO DE ALTA CALIDAD: UN CASO DE APLICACIÓN DEL PARADIGMA INDUSTRIA 4.0

1.- INTRODUCTION

In a world where the technology progress toward systems with more sensors, the capacity of having progressively more information about machines, processes and products has been historically associated to their own improvement. Hence, having machines that integrate a higher number of sensors leads to their own performance optimization, facilitate their maintenance and, thus, extend their useful life [1] [2].

Likewise, having productive processes that include a higher number of sensors and a better parameter control leads to obtaining products with a higher quality, together with reduced manufacturing periods [3]. In the same way, having a greater monitoring level over the manufactured parts, leads to an acceleration on the product development optimization, and, thus, to a significant costs reduction [4]

However, the monitoring capacity allows other more advanced technological options as well. Traditionally, these options have not been viable and provide new manufacturing opportunities as alternative to actuals solutions. In this case, submitted solution allude to an innovative vacuum fixture concept for machining of parts with different geometries.

Fixtures there have been a key element that has been developed in order to be adapted to the requirements demanded by the Industry. In terms of clamping requirements, low stiffness parts are among the most demanding cases, such as different structural elements on the aeronautical field. In these cases, the utilized fixtures are those based on a vacuum clamping system [5] and they are limited to a certain geometry. However, the actual trend based in the flexible manufacturing of small batches based on the "digital cloud" and in systems considered within the concept "*Internet of Things*" (IoT) [6] inhibit the development of dedicated fixtures for these emerging manufacturing environments [7].

In this context, a vacuum fixture based in the utilization of low cost flexible elements is presented. This fixture allows the clamping of parts with different geometries and provide a higher flexibility compared to the existing solutions. Thus, the investment cost is reduced, which facilitates the Industrial implementation. However, this development is just viable by the integration of advanced sensor and analysis technologies as they allow a continuous machining process and part condition monitoring.

2.- NEW FLEXIBLE FIXTURE CONCEPT

This innovative concept alludes to the fixtures that use flexible layers that function as support and vacuum clamping element for the different parts. Due to the machining application, the selection of the material is the key for the correct clamping of the product to be machined.

Due to the flexibility requirements in terms of adaptability to different geometries, the elastomers are a suitable option as they have a high strain capacity. On the other hand, due to the thermal changes produced by the cutting zone advance, the thermostable elastomers are a more reliable choice to maintain an acceptable geometrical accuracy. Finally, to transform the flexible layer into a vacuum table requires certain sealing properties that make the type R thermostable elastomers the ideal choice for the application.

In this case, the selected option has been a rubber employed in damping and sealing applications. These sort of layers, due to its own manufacturing processes, do not guarantee a proper shape accuracy. Thus, its application has been limited to applications where the required geometrical accuracy is over the 0.1 mm.

Nevertheless, due to the advance of the technique and the implementation of monitoring technologies, more and more solutions based on this very same concept are showed [8] [9] [10]. In these solutions, a layer type flexible element can be employed as a supporting and clamping element for its use as a fixture for different manufacturing processes.

2.1.- FIXTURES CLASSIFICATION

Traditionally, vacuum fixtures have been characterized by defining their accurate support, which allow them to obtain a high-quality machining. In the market exist rigid solutions and others capable of being adapted to different geometries. However, these commercial solutions continue to be hampered by their lack of flexibility in facing different geometries and by their high cost.

There are different fixtures classification [11]: based on their components, by their clamping system, by their configuration, etc. However, nowadays, there is no classification regarding the geometrical characteristics of the vacuum fixtures, as this aspect was implicitly related to their own adaptive capacity. Accordingly, a new classification (Fig. 1) is proposed embracing all the vacuum fixture solutions, including the concept studied in this article.

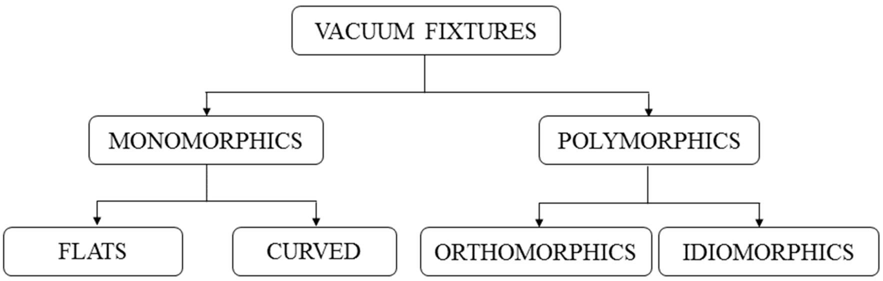


Fig. 1. Vacuum fixtures classification scheme.

As it can be appreciated on the previous scheme, the vacuum fixtures can be divided in two main groups: the "monomorphics" and the "polymorphics". The "monomorphic" concept refers to all the fixtures characterized by having their geometry unalterable over time. Most of these fixtures are flat vacuum fixture, even though certain manufacturers already offer ad-hoc solutions with the required curve. This sort of fixtures is characterized, not only by their lack of flexibility in terms of curvature, but for their fixture exclusivity for each product in high quality applications. This occurs due to the existing divisions between vacuum zones related to each associated machining operation. Thus, trimming and cutting channels or drilling holes can be included, as they are separated by seals that keep isolated the vacuum between zones (Fig. 2-a). Besides, it should be noted that, due to its uniform support over the whole part surface, these fixtures are employed in highly accurate operations, as high-quality milling.

(a) (b)

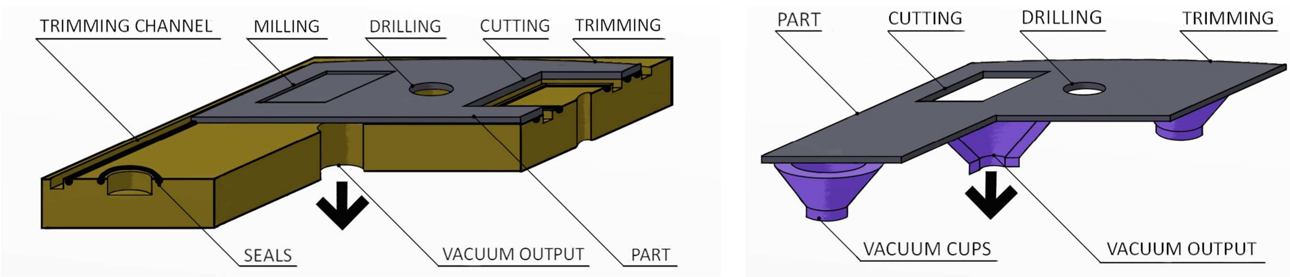


Fig. 2. Fixtures schemes: (a) "monomorphic" and (b) "orthomorphic".

On the contrary, all the fixtures capable of being adapted to different geometries can be considered as "polymorphic", i.e. they have or may have several forms. Historically, all the vacuum fixtures with the capacity of changing their own configuration were adapted precisely to the geometry to be machined. Hence the concept "orthomorphic", or, in other words, the capacity to maintain the correct form. These commercial fixtures are characterized by having a large number of actuators with vacuum cups that can be elevated to different heights so they can be adapted to several curve ranges (Fig. 2-*b*). Nevertheless, due to the low stiffness between each supporting zone, this sort of fixture is limited for applications where trimming and cutting operations are performed only, not for milling.

As alternative to the existing solutions on the market that are embraced under the concept "orthomorphic", "idiomorphic" fixtures are presented (*Fig. 3*). These fixtures are characterized by a high and unpredictable variability of thickness and form due to the manufacturing process of their flexible plates. Hence the term "idiomorphic", i.e. they have a unique and unrepeatable form.

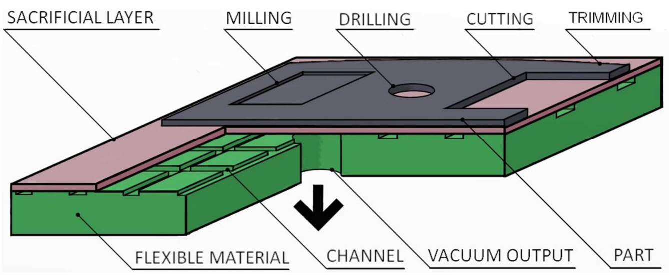


Fig. 3. "Idiomorphic" fixture scheme.

This sort of deformable fixture is characterized by distributing the vacuum forces all over the part through channels, guaranteeing a uniform clamping. On the other hand, this solution allows its utilization for the clamping of any part, regardless their contour, as they do not need any seal to maintain the air confined. In fact, for the applications where it is needed to machine though the part, as in the drilling process, it can be utilized any sacrificial layer that lets the air crossing, by being porous or by means of holes. Besides, as the local stiffness showed by this sort of elastic materials is enough against the low compressive forces experienced under finishing processes, it is possible to mill maintaining a good roughness on the pockets floor.

Unlike the "monomorphic" fixtures, this form is characteristic of each fixture, as it cannot be reproduced. However, in parallel, the flexibility provided by the elastomers allow "idiomorphic" fixtures to be adapted to different geometries, even though it is not the exact one demanded by the part, as with the "orthomorphic" fixtures. Nevertheless, there is a wide variety of parts that can be slightly deform without entering the plastic regime and with a correct clamping conditions.

It is in this point where the technologies developed within the Industry 4.0 frame allow the utilization of this sort of fixtures for the high accuracy machining. Through the use of sensors that monitor the part real position, it is possible acting on the toolpath by using a close-loop control. This way, the correct part form can be guaranteed.

2.2.- CHARACTERIZATION OF THE FLEXIBLE ELEMENT

Traditionally, the characterization of these flexible elements has been performed by searching their response against constants stresses [12] and against phenomena in which frequency has a great influence on the material strain [13]. In the manufacturing case the tool provides both, cutting and feed forces. However, in the

In this case, the survey is going to be focused in high quality machining processes, in which the tool spins over 12000 rpm [14]. Thus, the cutting forces application occurs at frequencies above 200 Hz. However, in the rubber-made "idiomorphic" fixtures the deformations derived from the loads applied at high frequencies can be neglected. This is an effect derived from the restriction on the material internal deformation an damping mechanisms [13]. As a result, the only loads to be considered are going to be those derived from the feed of the tool. In the drilling case, only the compressive loads will be contemplated, while for the trimming tests, just the shear stresses will be considered.

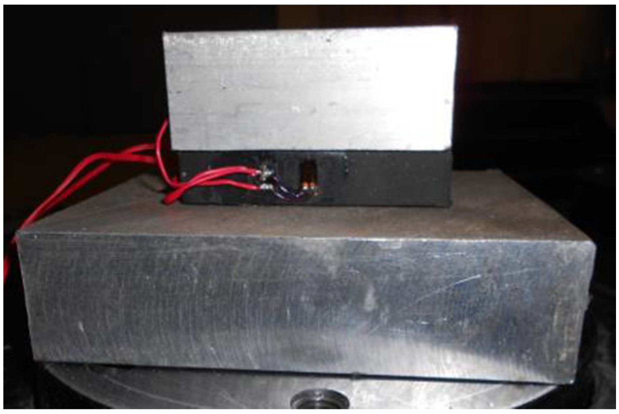
On the other hand, it will be considered that the different tool steps over each zone are separated each other the enough amount of time so the strain state can be assumed the same. Thus, it can be assumed that there is no accumulated deformation derived from the previous machining steps. Furthermore, it will be assumed that the temperature of the set and the material strain rate are constant over each step.

2.2.1.- Standard characterization

With the aim of characterizing the compression of these flexible layers, standards compressive tests have been performed by means of a universal machine E1/044 with capacity up to 10Tn. The used specimen has been a combination of a square rubber layer with a 45 mm side and 14.2 mm thickness, together with an aluminium block that, due to the low forces applied, it can be considered uncompressible. A extensiometric gauge has been placed along the rubber thickness and several load steps have been performed with a 1mm/min feed rate (Fig. 4-*a*).

First, measurements show that, from certain machine displacement on, the extensiometric compressive value falls, so its value is decoupled from the displacement and force increases (*Fig. 4-b*). This decoupling is due to the fact that the extensiometric measurement it is not reliable, as the lateral bulge suffered by the specimen distort data by introducing an important tensile strength component on the gauge that counters the real compression of the specimen.

(a) (b)



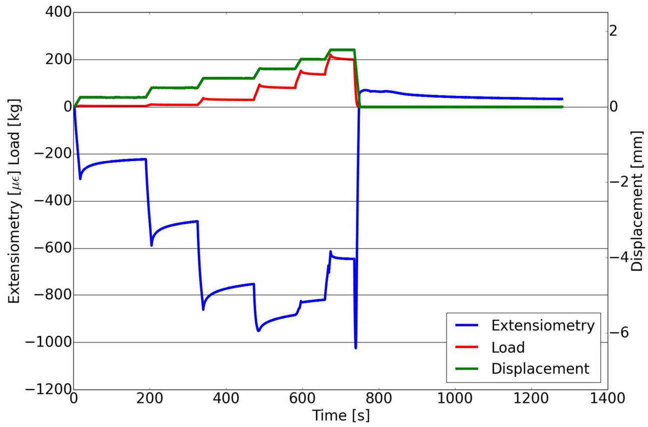


Fig. 4. (a) Specimen and (b) results of the standard compressive tests.

Apart from that, this test configuration ignores a key factor that has influence on the flexible layer behaviour: the preload derived from applying vacuum between the part and the fixture. This preload leads to being unaware of the rubber initial state. Thus, it is necessary to perform compressive tests that consider the fixture real compression derived from activating the vacuum.

2.2.2.- Ad-hoc characterization

For the *ad-hoc* tests, a “idiomorphic” vacuum fixture has been used by attaching it to a standard milling machine table. The vacuum fixture is square with a 300 mm side and 14.2 mm of average thickness. Over this fixture a 700 µm porous layer and an aluminium square block of 240 mm side is placed, that, as the previous tests, they can be considered uncompressible as well. The dimensions of the aluminium part are lower that the fixture size so the edge effect can be neglected. Finally, the part is clamped to the fixture with a vacuum pressure of -0.45 bar and to the machine head through an adapter (*Fig. 5-a*), so controlled movements can be performed both, axially and laterally. Besides, in order to monitor the real part displacement, a contact LVDT sensor is used, located in the upper or lateral part zone, depending on whether is a compressive or shear stress test. Thus, with this set-up the real behaviour of the flexible element can be characterized by considering the compressive preload generated by the vacuum application.

(a) (b)

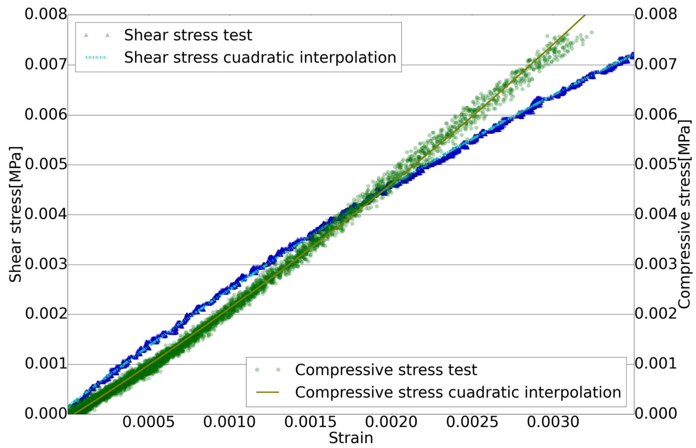


Fig. 5. (a) Ad-hoc test bench and (b)compressive and shear tests results.

Different compressive and shear tests are performed with a constant feed rate of 1mm/min as in the standard test. The tests have been sufficiently separated in time so the accumulative strain in the material can be neglected. Besides, due to the low forces, in order to facilitate the use of this data in upcoming analysis a linear regression can be utilized (Fig. 5-*b*).

2.3.- IMPLEMENTATION AS A VACUUM FIXTURE

With the results of the rubber *ad-hoc* characterization, different real machining casuistries have been analysed theoretically. The analysis is performed considering the relationship between the stress and the applied load through the part supporting area. On the other hand, the deformation is the quotient between the rubber compression and the initial fixture thickness. Thus, the error derived from the non-use of monitoring technologies can be estimated.

The analysis will be performed over two parts with different characteristics. The first one will be a lab-part, just like the one utilized on the *ad-hoc* characterization. The second one will be a low stiffness theoretical part defined based on the real requirements of the aeronautical skins [10]. For each case, the corresponding fixture is 14.2 mm thick. Besides, the fixture and the part area are considered with the same area. The selected conditions (*Table I*) have been the most demanding ones registered in the *ad-hoc* tests. In the lab-part case, for instance, they correspond with the tool feed forces registered in the machining processes of aeronautical alloys [15].

Part	Area [mm^2]	Thickness [mm]	Stress [MPa]	Load [N]	Compressive displacement [µm]	Shear displacement [µm]
Lab	5.76 x10^4	20	0.007	403	37	48
Aeronautical	14 x10^6	2		98000		

Table I. Selected conditions.

2.3.1.- Analysis in drilling operations

In the drilling case, the effect that it is going to be analysed is the springback occurred in the deformable material once the tool penetrates the part (Fig. 6). As it can be observed in the image, the fixture suffers an initial strain when the part is clamped and another extra strain when the drilling operation is performed. However, when the tool penetrates the part, a sudden form recovery occurs, as the fixture returns to the second step. Thus, if this retrieval it is not correctly characterized, the tool could penetrate the sacrificial layer as well and could damage the fixture.

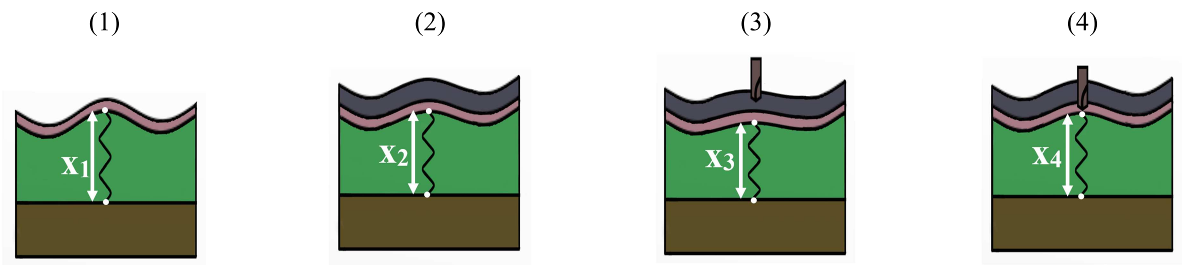


Fig. 6. Rubber strain steps throughout the part clamping and drilling, where $x_1 > x_2 > x_4 > x_3$.

The sacrificial layers have a great thickness variety. The most unfavourable case detected on the market is the one defined by porous layers with 700 µm thickness [16]. In the lab part, the selected stress conditions lead to a maximum displacement of 37 mm. Thus, the thickness range offered by the sacrificial layer guarantees the integrity of the "idiomorphic" fixture without monitoring the process.

With the aim of predicting the fixture compression in high deformation cases and based on the stress limitations of the *ad-hoc* tests, an estimation has been performed. This estimation has been calculated based on the quadratic extrapolation of the obtained data. Despite the different behaviours of the compressive rubbers based on the applied load range [13], it may be considered that any fixture manufactured in this sort of materials can be characterized with a stable evolution for loads under 1MPa [12]. Hence, its behaviour could be approximated through a quadratic interpolation.

Based on the quadratic interpolation (Fig. 5-b), obtaining a 700 µm compression leads to a 0.049 strain and a 0.46 MPa stress. If the same drilling forces are considered, the minimum area to press would be 876 mm^2. This area is approximately the area of a Ø32 mm tool feed force application directly over the fixture. Thus, in the case of drilling low stiffness parts with low diameters tools, it will be necessary to monitor the process in order to avoid any fixture damage.

2.3.2.- Analysis in cutting operations

In this case, a similar analysis to the drilling one has been performed, but in this case, taking account the shear stresses. The same happens when the tool trim a part section. In this case, if an inner part section is going to be cut, when the trimming loads are over, the machining stresses disappear suddenly. This leads to an abrupt lateral part displacement.
In the previously introduced aeronautic case, in order to obtain a 48 µm displacement 98 kN are needed. However, even though this error may be critical, this load level is higher than the existing ones on the skin machining [10] or other similar applications [17]. Hence, it can be estimated that in real cutting applications the springback due to the tool feed will be limited.

However, in the lab part case, in order to obtain a similar displacement, it would be just necessary a 403 N shear force. These forces are easily obtainable on the industry [17]. In this case, for milling and lateral trimming, under agressive conditions and with small parts, it will be necessary adding a monitoring system in order to machine the part within tolerances.

3.- SYSTEM CAPACITATION FOR HIGH QUALITY MACHINING

In the previous section, different machining processes applications have been analysed over an "idiomorphic" fixture. In both cases there have been proved that, without monitoring, its implementation in certain industrial applications is feasible. However, most of the applications in which a vacuum fixture is needed are referred to cases where, besides trimming and drilling, parts require certain milling operations.

Therefore, for complex parts, for instance, aeronautic parts, the initial characterization of behaviour of the flexible element it is not enough. This happens due to the vibrations and deflexions appeared in the part during the milling process [18], even when using a flat vacuum table. In most of the cases, these phenomena can be solved through the machining conditions tuning [19]. However, in the cases where a flexible element is used as a fixture, its own profile variability leads to errors in the machining that are not solvable through the machining conditions, but through the toolpath adaptation.

For instance, when a trimming operation is performed, if the rubber profile variability is higher than the thickness of the sacrificial layer, then it is necessary to raise or sink the tool in order to continue with the machining process without damaging the fixture. Similarly, if a part zone has to be milled, and a tough thickness tolerance is required, it is necessary to monitor the position of the part. Hence, in such cases, it is needed to add a monitoring system able to measure the part position so it can be act online over the toolpath, as it is done in different industrial developments [20] [21].

In this case, an initial analysis has been performed to quantify if the interferences related with the chips existence could be comparable to the changes in the flexible element thickness. The selected task has been groove milling. The tests have been performed with a 10mm diameter spherical tool, with a 75.4 m/min cutting speed and a 0.06 mm/tooth feed. For the tests, an Acuity AR200 laser has been attached to the milling machine head, so it can monitor in front of the tool along the different linear trajectories (*Fig. 7-a*). In order to have a representative sample, five different repetitions have been performed, covering several zones with different chip densities. The acquisition frequency in all tests has been 1000 Hz.

To these measurements a moving average based filter on the time domain has been applied to the laser signal. The output $y[n]$ is the mean value of the last M samples:

$$y[n] = \frac{1}{M}\sum_{k=0}^{M-1} x[n-k] \qquad (1)$$

This sort of Finite Impulse Response (FIR) filters are the most frequently employed ones when processing time spectrum signals due to their capacity of reducing random noise [22]. In this case, they are useful for chip identification along the part profile. Thus, with the aim of performing a reliable adjustment, different filtering levels have been analysed. Each filtering level is related with the number of points M considered on the moving average calculation (*Fig. 7-b*).

Finally, for each test, the maximum error between the profile without chips and the obtained signal through the moving average have been compared (*Fig. 7-c*). This analysis has been performed for each filtering level and the obtained error have been compared with the thickness tolerance limit required on applications such as the aeronautical [10]. The result shows that, signal accuracy under 25 µm can be obtained by software, regardless the chip existence between the sensor and the part. Thus, this filtering method could provide enough accuracy so it can be applied in high quality machining applications.

a) (b) (c)

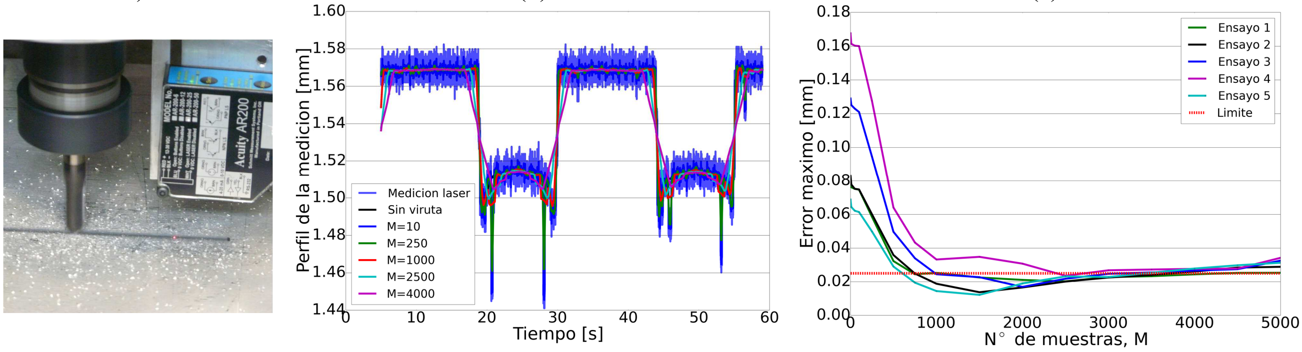


Fig. 7. (a) Laser monitoring test bench (b) filtering with moving average of the chip interferences and (c) tolerances comparison.

4.- CONCLUSIONS

This work has been focused in the presentation of an innovative vacuum fixture concept that rises from the search for more eco-efficient solutions and that, with the implementation of the Industry 4.0 paradigm, it is catapulted as an alternative to highly technological solutions.

First, a classification that includes this new sort of flexible solutions has been proposed so the idiosyncrasy of each kind of existing fixture can be clarified. This classification has come in handy as starting point for highlighting the different characteristics that add value to the proposed fixture:

- Eco-efficiency: It is a low-cost solution compared with the existing industrial solutions.
- Flexibility: It is vacuum fixture adaptable to different curves that, besides, it allows clamping different parts, regardless the geometry of their contour.
- Versatility: It allows interleaving, under the same set-up, trimming, cutting or drilling operations together with others with higher geometrical requirements, such as milling.

With the objective of validating its behaviour under compressive and shear stresses, the elastic material that form the fixture has been characterized. Thus, its behaviour under the stresses derivated from the different machining processes has been analysed. Nevertheless, this analysis it should be completed through real machining characterization and by studying the effect of different system parameters, such as, the elastic material composition or the fixture thickness.
Finally, the frame in which the concept impact is amplified through the process monitoring has been defined. Thus, by employing laser technology the part position can be monitored, regardless the existing chip density and by maintaining the linearity in the measurements of the most challenging industrial applications.

FOR DEEPER KNOWLEDGE

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