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Accessing the cutting forces in machining processes: An overview

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Abstract

Machining processes remain an unavoidable technique in the production of high precision parts. Tool behavior is of utmost importance in machining productivity and costs. Tool performance can be assessed by the roughness left on the machined surfaces as well as of the forces developed during the process. Depending on the machining process, different types of dynamometers may be adopted. This technique has often been used by numerous researchers in this area. This paper aims to make an overview of the different techniques and devices for measuring the forces developed in machining processes, allowing a quick perception of the advantages and limitations of each technique, through a literature research carried out using recently published works.

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1. Introduction

Regarding the demand for high precision parts coming from growing industries, such as, the aerospace, medical, automotive and electrical industry [1], the CNC Machining market as seen a considerable growth in the last six years, and is expected to keep growing, projected to be a \$100B industry by 2025 [2]. Leading the charge in the use of CNC Machining processes and machines, are countries like India, China, Japan and other countries of the Asia Pacific area [3].

This continuous growth provides a motivation to improve on these machining processes, from a manufacturing point of view. The monitoring of cutting forces during the machining processes has been of utmost importance to improve and optimize these. Measuring these forces can give information on the material machinability, as well as optimal process parameters [4-5]. Tool behavior can also be monitored by measuring cutting forces [6], thus, tool optimization is also possible [7], but there are other parameters that need to be

considered. Additionally, the knowledge of these cutting forces enables the control of some processing problems in the machining process, such as, chatter vibration, overload and tool condition [8]. Another advantage of monitoring these forces, is that improvements can be made, regarding tool-geometry or even tool-choice (coating choice for the correct application). A wrong application, or a poorly optimized process will influence the cutting forces that are generated during the machining process. Having the knowledge of how these forces influence the machining process is important when it comes to process optimization, as these impact directly certain aspects, such as, surface finish quality, tool-life and energy consumption.

There are different ways of determining these forces, either these are determined using a sensing system or by applying an analytical method. However, there are many different sensing systems and cutting force measurement systems (dynamometers).

In this paper, a review of recent published articles, regarding cutting force measurement/determination during machining

was done. The most recent and novel methods that are being employed in this area are going to be mentioned and presented, additionally, the advantages and drawbacks of each method are going to be described. Furthermore, the recent advances that are being made on cutting force measurement and determination are going to be presented in the last section of this article.

Nomenclature

CNC	Computer Numerical Control
MRR	Material Removal Rate
FEM	Finite Element Method
ML	Machine Learning
CFRP	Carbon Fibre Reinforced Polymer
CNN	Convolutional Neural Network
ANN	Artificial Neural Network
ANOVA	Analysis of Variance

2. Literature review

In this chapter, some recent advances in cutting force determination methods are going to be presented, whose were taken from recently published works. There are mainly two ways of determining cutting forces, either by employing an analytical or numerical method [9], or even using the Finite Element Method (FEM) [10], or by using a force sensing system, such as a dynamometer to monitor cutting forces during a machining process, directly or indirectly.

The main difference between direct and indirect measurement of cutting forces, when applied to sensing systems, is the parameter being monitored. For example, the cutting forces can be derived from the measurement of current consumption of the machine's driving motors, whereas the direct measurement of these forces can be achieved with different types of dynamometer such as: piezoelectric, capacitive, optoelectrical and strain gauge. These types of dynamometer track a certain change in a parameter due to the cutting force [11].

In this chapter the different methods are going to be separated, then some recent papers on the subjects are going to be promptly presented. Some advantages and drawbacks of each method are also going to be mentioned. The different methods are Numerical, Force Sensor, Machine Learning and Robotic Machining.

The numerical and force sensor methods are already quite known. There is still research being made on these matters, and so, there is a continuous evolution of the applications of these methods, from using numerical methods as a complement for force sensing systems, to the development of novel dynamometers for reliable, low-cost cutting force measurement. These methods are also employed (alone or both), in the optimization of machining processes. By improving on the quality of the produced part, or by prolonging the lifespan of the cutting tool. Furthermore, the optimization of a process makes it cheaper, by reducing energy consumption or, as mentioned, improving the tool's lifespan, thus, reducing possible tool changes.

Regarding machine learning and robotic machining, these are quite recent in the field of cutting force measurement, but

they look quite promising, so they were included in the research made to make this overview on the determination of cutting forces in machining.

2.1. Numerical Methods

Purely numerical methods for the determination of cutting forces are generally used for the prediction of these forces. The prediction of cutting forces is used to optimize certain processes, such as the machining process of gear skiving [12], or even the prediction of cutting forces in flank milling 5-axis operation [13]. This process optimization may range from, wanting a higher material removal rate (MRR), or a better-quality surface-finish, to improve the lifespan of the tool. There is a growing need for these processes, as the complexity of some machining processes, specially 5-axis machining, presents some problems, as the ever-changing geometrical parameters of the cutting area. This interferes with proper data collection, that some analytical models propose to solve [9].

Regarding cutting parameter optimization, using cutting force prediction, the paper presented by Sagar et al. [14], proposes a method for the prediction and optimization of cutting forces, using Oxley's predictive theory and the Response Surface Methodology (RSM), in the machining of Tungsten heavy alloys (WHAs). The authors employ these methods to predict the cutting forces at different feed and speed combinations. The schematics of the methodology, used by Sagar et al., can be observed in Fig. 1.

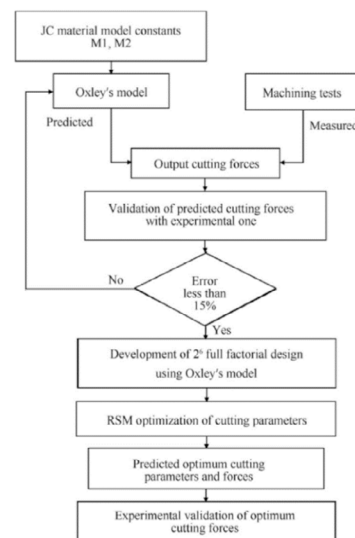


Fig. 1. Scheme of the methodology adopted for the prediction and optimization of cutting forces [14]

An analytical cutting force model was successfully developed and verified by comparing the different cutting force components with experimental data. Furthermore, it was found that the feed rate was the most influencing parameter in the cutting force. Optimal values for cutting speed and feed rate were also found, showing that methods such as these are quite useful in the optimization of machining processes.

FEM has also been employed in recent years for the prediction of cutting forces [15–16], enabling the prediction of surface roughness. This is very useful, as the process can be optimized in the simulation stage, not risking the waste of material/tools of making multiple tests, when using cutting force sensors. This method can be used to optimize the machining process of certain materials, giving information relative to tool temperature and chip morphology. Thus, this information can be used to optimize cutting tools. With information on the tool temperature and coupled with the cutting force values obtained, the tool's wear throughout the process can be analyzed. This provides the opportunity to choose the best machining parameters, such as lubrication type, in order to improve the tool lifespan for roughing operations or lower surface roughness values for finishing applications. Regarding the optimization of cutting tools, in the turning processes. For example, different nose radii influence the cutting forces generated during machining. If these radii are smaller, then the cutting forces generated will be higher [17–18]. The study, already mentioned, by Yameogo et al. [19], presents a method for the prediction of cutting forces and chip morphology by using a 2D FE model. The authors establish a link between chip morphology and amount of cutting forces. Studies such as these are important, in order to have a better understanding of how certain parameters influence the generated cutting forces.

The FE method enables the understanding of the development of cutting forces in relatively new processes, such as, high speed diamond turning and milling, in which a study on these processes reveals that there are quite a few advantages of these processes relative to standard diamond machining. A recent study has revealed that the machining time, cutting forces would be reduced when employing these processes over the standard diamond machining process, which would improve the cutting tool's life [20]. Nowadays, FEM is also being employed in the machining of composites. Some studies are using this method to assess the effect of tool wear on the machining forces of a CFRP (Carbon Fiber Reinforced Polymer). Moreover, these methods allow the obtaining of useful information for developing new cutting tool geometries for machining that can further improve the machining of these materials [21].

Numerical or mathematical methods have also been employed in the fine-tuning of cutting force measurements obtained from force sensing systems. The data collected by these devices can be incorrect due to certain parameters, as the cutting area geometry being too complex, outside interference such as vibration, or even machining frequency. There are studies, such as the one presented by Venkatesan [22], which has employed the Taguchi Method to determine the optimal machining conditions in a laser assisted machining process of Inconel 718. The data regarding cutting forces is collected by a dynamometer. The authors optimized the process, focusing on the decreasing of cutting forces during the material machining. This study highlights the potential of cutting forces knowledge in these machining processes. Still regarding cutting force compensation, Wang et al. [23] propose a method for frequency response function (FRF) modelling based on transfer path analysis (TPA) and receptance coupling substructure analysis

(RCSA). The FRF is required for cutting force compensation, as these forces are difficult to measure accurately, due to the dynamic characteristics of cutting forces measurement systems. The authors obtained a verified model that could be used for FRF prediction, conducting milling tests for algorithm verification. However, although the FRF of the workpiece can be obtained by FEM, for various geometries, the FRF of the dynamometer needed impact tests in order to obtain the parameters. This method presents another effective way of predicting/controlling the cutting forces of a machining process. Although this method still needs improvements, it can be applied to both turning and milling machining processes, enabling its optimization.

There are also cases where a numerical method is used to correct the signals obtained from cutting force sensors, as in the study of cutting force measurement correction obtained with a table dynamometer. Frequencies from the machining process can interfere with the readings from the dynamometer. Thus, Wan [8] proposes the use of a Kalman filter to correct the force measurement, achieving a successful implementation. The data may also be insufficient, then a hybrid measurement method can be employed. These methods are coupled with force sensing systems to give detailed information impossible to be provided by the dynamometer, for example, tool temperature. The work performed by Daniyan et al. [24] presents a solution for optimizing the milling of AISI P20 steel. In the presented study the authors employed a dynamometer to collect cutting forces during the milling of this material. A process simulation was carried out using Complete Abaqus Environment, in order to know the temperature distribution over the tool (Fig. 2c), workpiece (Fig. 2b) and tool-workpiece interface (Fig. 2a) during machining.

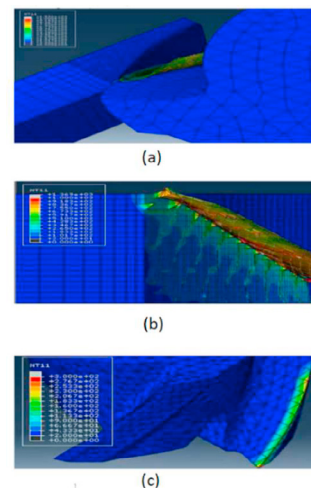


Fig. 2. Temperature distribution on the tool-workpiece interface (a), workpiece (b) and tool (c) [24]

Additionally, Response Surface Methodology was employed to study the interactive effects of the cutting speed and feed rate. With all this information, the authors created a way to optimize this milling process, achieving a better material removal rate and surface finish, if the feed rate and cutting speed parameters are changed.

Still regarding methods that employ both analytical processes and force sensor methods, Kene et al. [25] presents a study about the development of an analytical model for the monitoring of tool health in hard machining. The model uses data from three sensors. The cutting force (provided by a dynamometer), the tool vibration (provided by an accelerometer) and the surface roughness (surface roughness tester). Furthermore, the optimal machining parameters (cutting speed, feed and depth of cut) were determined and used. All this is used to create a fusion function that can be used to predict the tool's wear, with an error percentage below 9%.

In the study performed by Orra et al. [26], a mechanistic model for the prediction of cutting forces in the turning of AISI 52100 and AISI 4340 steels is proposed. The cutting forces are predicted with the information provided by chip morphology and nose radius influence on it. The method was successfully validated for these two materials. Furthermore, the model achieved a confidence level of 95%, accurately predicting cutting forces and providing a viable and economic way for the prediction of cutting forces, at least for these two steels.

There is some recent research made in the study of cutting forces in the ultrasonic assisted milling process. In the study carried out by Verma et al. [27], a statistical model is presented, which evaluates the effect of process parameters, on the cutting forces generated during the process and the effect on the cutting force deviation. The evaluated parameters were, the power of ultrasonic vibration, rotational speed, axial depth of cut and feed rate. Milling tests were conducted on Al6063, then an ANOVA was performed to obtain the regression equations. The results obtained from the milling tests were analyzed to study the effect of the parameters on the cutting forces. The authors validated this model and found that the parameter that influenced the most the cutting forces was feed rate. However, the parameter that influenced the cutting force deviation was rotational speed. Additionally, the authors determined the best parameters, in order to obtain the lowest cutting force values during the machining of the aluminum alloy.

These methods prove to be a cheap approach, when compared with expensive dynamometers. However, these methods also present some drawbacks, such as, time constraints and the need to know the proper inputs, especially in case of simulations. Numerical methods are frequently paired with other cutting force measurement devices, either to correct force measurements, making these readings more accurate, and they complement force measurement systems, to obtain a more detailed information on cutting parameters and tool health, enabling the optimization of these machining processes, either by improving surface finish quality, tool-life or even cycle-time.

2.2. Force Sensor Methods

These methods are the predominant choice for cutting force measurement and are usually paired with numerical methods as a method for validation.

As previously mentioned, the monitoring of cutting forces is of great importance, not only to improve/optimize the machining process, but to gain insight on the cutting behavior of some tools, or even achieve knowledge on the machining

process itself. Furthermore, cutting force determination/monitoring can bring the improvement of some cutting tool technology, such as the use of new types of coatings for cutting tools, or even studying the influence of novel geometries, and how these will affect the cutting forces generation.

There are two ways of determining cutting forces using sensors, either indirectly or directly.

Indirect cutting force measurement is achieved by monitoring parameters that are related to the cutting force, changing to some degree. Depending on the cutting force, some examples of these parameters are, spindle motor current, voltage, acoustic emission, and vibration [11]. In the case of a recent study [28] on indirect cutting force measurement, cutting force values are achieved based on tool flank deflection. A displacement sensor is attached to a tool shank and used in a cutting operation. The data collected is the deflection signal, which is then filtered and used to calculate tool stiffness, being usually used in turning processes to obtain the cutting force values. This is very important, as obtaining reliable readings of cutting forces is very useful for the selection of proper machining parameters and tool geometries. The cutting force values were compared with the readings of a dynamometer (Kistler 9255B), the experimental procedure is represented in Fig. 3. It was concluded that the method presented by the authors was reliable in obtaining the cutting force values. Due to the simplicity of this method, it proves to be a very friendly method, being able to be applied to a workpiece of any size.

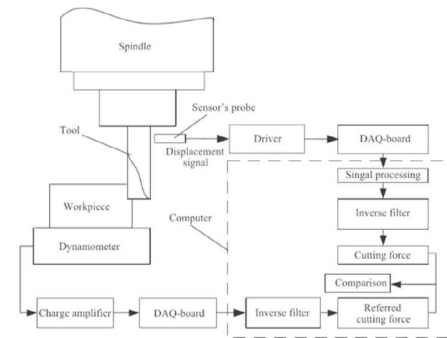


Fig. 3. Experimental procedure for the measure and comparison of cutting forces during machining [28].

The direct sensing methods are those that employ effects that are directly related with the cutting forces, such as, mechano-magnetic, mechano-electric and mechano-optic conversions [11]. These sensors are dynamometers, and they are the most used devices for cutting force measurement. These range from optoelectronic and piezoelectric dynamometers to strain gauge and capacitive force sensing systems. With the knowledge of the cutting forces provided by these devices, the optimization of certain machining processes and the machinability of certain materials becomes possible. In this work performed by Daramola et al. [29], the optimization of the machining of Ti-6Al-4V is studied and the cutting forces are obtained using a piezoelectric dynamometer. The goal of the authors was to minimize the resulting cutting force during the machining of this material. Thus, they were able to successfully set parameters on how to reduce the cutting force

during machining based on those results. These dynamometers can also be applied on studies related with machining lubrication. In this case, a study [30] was conducted for a turning operation of a low carbon steel (St52-3), using a multi-component dynamometer (Kistler 5070) to gather the cutting forces generated during the turning process. The tests were conducted under Minimum Quantity Lubrication (MQL) and the authors concluded that under this condition the machine consumed less power. In addition to the low quantity of lubricant used, this means that this lubrication method has some advantages when used for the machining of low carbon steel. In order to develop tools that perform better and longer, tool manufacturers study tool's cutting behavior. Dynamometers are employed in the study of the behavior of these tools in various machining processes. The knowledge of these forces is also beneficial to the understanding and development of new coatings. Some of these coatings are employed to reduce cutting forces, improving the surface roughness of the workpiece and increasing work-life [31–32]. Knowing these cutting forces is, as previously stated, important when trying to optimize a certain process. Cutting force measurement and analysis can also be used to compare coating performances, thus, choosing the best suited coating for the application. For example, in this study performed by Gupta et al. [33], in which the cutting characteristics of three PVD (Physical Vapor Deposition) coatings are analyzed and compared in the turning of C45 steel, the coatings that were being analyzed were TiN, TiAlN and AlCrN coatings. Thanks to cutting force information and hardness measurement, a relation between cutting force and depth of cut was established, and the coating with the best wear behavior was determined. The TiAlN coating, with its lubricating ability, lowered the cutting forces generated when turning the C45 steel. Studies such as these highlight the importance of cutting forces knowledge. However, this can be used not only for process parameter optimization, but for tool coating selection.

There are some recent developments on types of dynamometer, such as, a novel triaxial optoelectronic based dynamometer, presented in the Subasi's work [34], in which the authors describe the development of a compact and triaxial dynamometer that uses photo-interrupters. This dynamometer can detect forces in three orthogonal dimensions, and is presented as an alternative to current dynamometers, being a compact and relatively cheap solution. In another paper [35], a displacement-based dynamometer for milling force measurement is proposed. A flexure-based strategy was implemented in the milling setup, where structural deconvolution was carried out by filtering the measured displacement signals. Cutting force measurements were successfully obtained when using this approach, for both Single Degree of Freedom and Multiple Degrees of Freedom flexure-based dynamometers. Otherwise, Sandwell et al. [36] presents the development of a multi-degrees of freedom optical table dynamometer. In that paper, the development and implementation of an optical force dynamometer is described. A four-quadrant position sensitive photodiode is used to detect the position of a target surface to estimate the applied force in three independent directions. The use of this single detector minimizes the overall cost of the system. Multi degrees-of-

freedom measurements are permitted without significant loss due to the implementation of a novel decoupling algorithm and oscillator detector scheme.

In the work carried out by Transchel et al. [37], a dynamometer for the measuring of force signals in the micro machining operations is presented. The sensor presented is a piezoelectric dynamometer (MicroDyn). Due to the high rotational speeds, characteristic of the micro machining process, there is high excitation frequency. This frequency interferes with cutting force measurement, making it impossible with regular commercially available dynamometers. The authors have tested the dynamometer, which enables the measurement of forces in high dynamic cutting process with frequencies up to 5 kHz.

Still regarding the development of dynamometers, in the work developed by Totis et al. [38], the development of a table dynamometer for advanced milling and drilling applications is presented. The dynamometer was designed for precise milling and drilling, with small cutters and at high spindle speeds. The device can measure the three resultant components of cutting force. Additionally, the dynamometer can measure cutting torque in the drilling operations. This device has an extended range of measure, when compared to the most accurate dynamometer table commercially obtained. Furthermore, this device has an excellent dynamic behavior, i.e., it can measure cutting forces accurately at relatively high frequencies (generated by high spindle speeds). In another study, the development of an integrated rotating dynamometer on a tool holder is presented by Rizal et al. [39]. The developed dynamometer, was a strain gauge-based rotating sensor, directed primarily to the milling and drilling processes. The novelty of this dynamometer comes from the fact that the tools are interchangeable, which are compatible with different standard modules, making this a very flexible system, with easy reconfiguration. The device measures force up to 3000 N and supports rotations up to 5000 rpm. The authors report that the cross-sensitivity errors are below 4.05%, which is an acceptable value. This dynamometer can be applied to cutting process optimization, machine tool monitoring and design. This coupled with the high flexibility of this device, makes it very appealing.

The papers mentioned previously [34–36] state the importance for a cost-efficient alternative to the force sensing systems. Dynamometers provide mostly accurate cutting force measurements, whose can be obtained very quickly when compared to the numerical methods, which in turn, enables the faster analysis/optimization of a machining process. The accuracy problem of these measurements can be corrected, as stated previously, using numerical methods. However, the price for these devices is still quite high, adding a barrier of entry, especially in this field of research. With the monitoring of cutting forces being so important for process optimization or tool-life monitoring, there is a need for a lower-cost alternative to this equipment, so that more research can be performed. Another drawback besides the price is, that these dynamometers interfere with the system where they are implemented, i.e., the device stiffness and assembly itself affect the cutting force measurements, so there is the need to implement some form of correction method, by figuring out a

better setup (that would not interfere with the cutting force readings), or by developing new types of force sensors, with the aim to minimize these problems.

2.3. Machine Learning Methods

Machine Learning Methods are being employed in the determination of cutting forces. Generally, a machine learning model is utilized to acquire information from various sources, such as machining operations (milling, turning, etc.) and obtains data from numerical methods, such as finite element method. This enables the prediction of specific cutting forces on similar operating conditions. Machine learning can also lead to cost and time savings, increased quality, and material waste reduction [40]. In the work performed by Wenkler et al. [41], it is described the possibility to record and predict cutting forces from a milling process. Data is obtained from a monitored milling process; these data values are collected in a database. An Artificial Neural Network (ANN) is trained, which predicts the specific cutting force. If predicted forces have a large deviation, a control loop ensures that the ANN is relearned with the extended data basis. This enables the evaluation of a capability of a machine to execute, before performing its task. The authors also state that this model should be used as a base for further analysis of different cutting processes, such as, drilling and turning [40]. Another paper presents a hybrid approach of data collection, when using machine learning to predict cutting forces considering tool wear in a turning operation [42]. Here, data is collected from both a dynamometer and a 2D FEM model, which enables this machine learning model to predict not only cutting forces but also tool wear, thanks to the 2D FEM model, as seen in the model depicted in Fig. 4.

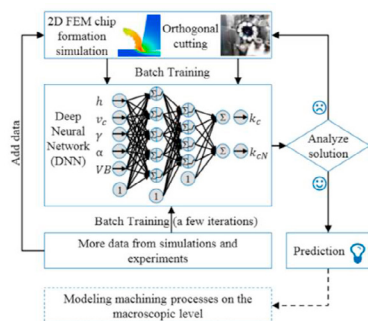


Fig. 4. Hybrid approach on machine-learning architecture [42].

In the study accomplished by Gouarir et al. [43], a system for tool wear prediction based on machine learning (ML) techniques and force analysis is presented. This system uses a force sensor to monitor the wear progression of the tool flank. Furthermore, it uses ML with a Convolutional Neural Network (CNN) to predict tool wear. The tests that were conducted were the milling of a stainless-steel workpiece using a ball end mill, in dry machining conditions. The ML model uses a database which contains information of previous experiments. The authors report that the CNN can identify the correlation between the cutting forces and the tool flank wear, achieved without any filtering methods. If the data is available, the

prediction of tools wear can be made for any tool and any material. This also means that the effectiveness of this method is dependent on reliable data. Furthermore, the cost of this method is very high, especially due to the sensors utilized in the cutting process. However, it is a very simple method to implement, with highly accurate predictions. These methods are still quite new and very dependable on a reliable database. Moreover, they are still quite slow when it comes to cutting force prediction mainly due to the data collection, specially data from FEM models, as these are very time consuming. Although, machine learning methods show a very promising future, predicting the best machining parameters and tool wear, boosting the machining processes productivity.

2.4. Cutting Force Determination in Robotic Machining

Robots are already implemented in industrial machining operations that involve relative low cutting force requirements. Robots bring many advantages in the machining area; they can be implemented with analytical or numerical models in order to improve tool path accuracy. Sensors can be easily implemented on a robot, which makes these robots adapt their actions depending on the sensor data. The opportunity to implement machine learning models is possible, because robots able to learn and adapt its behavior depending on the data acquired throughout the machining processes. Robots may even present a lower cost, in long term, when compared to machining centers. Thus, coupled with the opportunity to improve machining accuracy for robots gives them a significant advantage in machining tasks. Additionally, robots are flexible and able to perform different machining tasks [44]. There are some papers about using robots for the determination of cutting forces. As stated previously, sensor implementation on robots is quite easy, yet there is a need to study the effect of the robot dynamics in the machining processes. The work performed by Cen et al. [45], studies the effect of robot structural vibration, and cutting forces in a robotic milling process. Studies like this are a necessity for a better understanding of the forces developed in robot machining, as the easy sensor implementation in robots, and their autonomy to correct and adjust the process, reveals promising applications on the area of the machining processes. Another work carried out by Rivière-Lorphèvre et al. [46], proposes a 2D1/2 model approach to compute the cutting forces in milling if the cutting tool axis is tilted. This enables a more accurate prediction of cutting forces for multi-axis machines or robotic machining.

This study carried out by Slamani et al. [47] studies the effects of machining parameters on cutting force components, during high speed robotic machining of CFRPs. The authors created a model for the prediction of cutting force components, for different cutting speeds, feed and robot configuration. The model was then validated based on the experimental data. The authors report that the created models are valid, in the prediction of cutting forces for this application. Studies such as this, enable to calibrate machining process to optimize cutting forces generated. The reduction of these leads to an overall better-quality work, in this case it avoids the delamination of the CFRP. Furthermore, it reduces the robot deflection and the

tool wear suffered during the process. The robot configuration is also very important, including the number of joints, or the motion of the robot. With the cutting force knowledge this can also be optimized in order to achieve the desired results, such as, optimal robot configuration, optimal task placement zones (based on robotic arm reach) and robotic machining motion, which can lead to lower cutting forces [48–49].

Robotic machining reveals a great potential relative to work productivity, tool wear optimization and overall machining time reduction. The ability to easily implement sensors on robots, enables for a better interference-free cutting force measurement in machining processes. Robots ability to correct in real-time machining parameters and learn (when coupled with machine learning models) as they work, provides an attractive alternative to the traditional CNC Machining processes. Currently, numerical methods are being developed to predict cutting forces in multi-axis machines and robotic machining. However, these still needs validation and cutting force measurement is still, mostly achieved, by using dynamometers implemented in conventional machining setups.

3. Summary

The current trends for each of the methods presented in this overview are as follows:

- Numerical Methods – Although these are a cheaper alternative to other conventional cutting force measuring systems, they are still very time consuming. They are usually paired with force sensing devices, in order to complement or correct the analysis made by these devices. There is, however, various studies on the prediction of these cutting forces for more complex machining setups, such as 5-axis machining and robotic machining. These methods present a very good opportunity to the optimization of certain machining processes and the recent developed researches have yielded satisfactory results. However, the biggest drawback, as mentioned, is the necessity of both methods (force sensor and analytical) in the determining of cutting forces.

- Force Sensor Methods – These methods employ sensors to monitor cutting forces, either directly or indirectly. There have been developments on indirect measuring methods, such as, using displacement-based measuring devices. Due to the current high price and actual device geometry that influences cutting force measurements, a need for low-cost, compact alternatives is arising. However, these sensors are still widely used in the machining industry, and in recent research, especially in the optimization of machining processes, by aiming to reduce cutting forces and improving overall surface-finish quality and tool lifespan.

- Machine Learning Methods – Machine learning models show high promise in predicting cutting forces. This approach is quite novel, and it can be seen in the use for cutting force prediction, by using data provided by various sources. These sources can be provided by previous machining tests, such as values from dynamometers readings and simulations. These models need, however, a reliable data source, which can be provided from multiple sources, even from FEM models, enabling the understanding of chip morphology, tool/workpiece temperature, thus providing a better

understanding of tool wear. This is very appealing, as it permits the quick optimization of certain machining processes. The more data that is collected, the more reliable the predictions of these methods are.

- Cutting Force Determination in Robotic Machining – with the increasing use of robots in machining, it makes sense that there is also a need for monitoring cutting forces in these processes, in order to optimize them. Easy sensor implementation, and high versatility of the robot, enables process monitoring and correction in real-time. However, there is still much room for improvement on this matter, as the robot itself influences the readings of cutting forces taken in robotic machining. These interferences are usually due to vibrations of the robotic arm. Yet, the possibility of process monitoring/optimization in real time, coupled with the high productivity of this process, makes robotic machining an attractive choice over conventional machining, and thus, controlling the cutting forces and machining parameters of robotic machining is a current focus for the machining manufacturing industry.

The recent methods that are being developed, from numerical methods to novel dynamometer types, seem to focus on the delivery of a cheap cutting force measurement method, as an alternative to the expensive dynamometer and sensor systems, making research on the cutting force knowledge more accessible, enabling the development of process parameters for hard-to-machine materials, and optimization of tool performance and work-life.

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