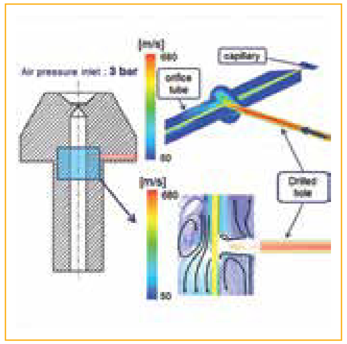
AIR-ASSISTED WATER JET CUTTING TECHNOLOGY

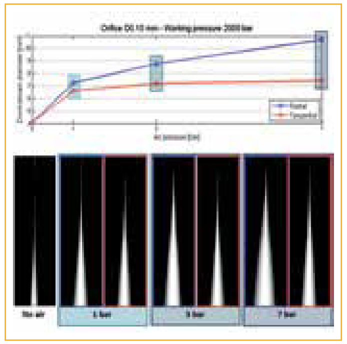
Francesco Arleo - Supervisor: **Prof. Massimiliano Annoni**

The core of the present work is the water jet orifice which is considered the heart of the technology and for sure one of the most important component whose behavior directly influences the process performances and reliability.
First of all, CFD-aided studies on the orifice outflowing regimes and jet stability are carried out aiming at a deeper insight of the complex fluid dynamic phenomena taking place inside the orifice and outlining the main causes of perturbation and process instability.
Briefly, the loss of coherence happens when the source of perturbation reaches the orifice capillary causing a loss of the hydraulic flip condition.
Afterwards, a solution is studied in order to reduce and control the previously mentioned instabilities.
This solution consists in a controlled air flux blown inside the orifice tube thanks to a small hole linked to the outside ambient through a modified cutting head retaining nut.
At the beginning, the proposed solution is tested again by means of numerical simulations showing promising results: supplying pressure enough, the forced air flux is able to coherently modify the inner velocity field, preventing any disturbances to reach the capillary region thus ensuring



1.Numerical results of the proposed solution.

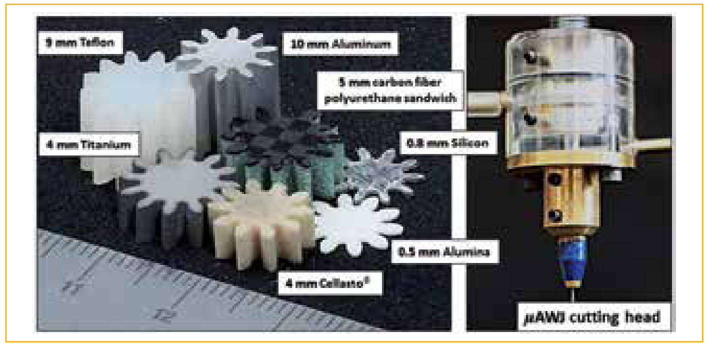
the jet stability over any working condition (Figure 1); moreover, by increasing the air intake pressure it is also possible to modify the jet spreading in a controlled way, making it able to adapt the jet structure to any specific application.
This gives the birth to the Air-Assisted Water Jet cutting technology.
The air-assisted orifice concept is then tested practically by designing an Air-Assisted Pure Water jet cutting system prototype whose performances are characterized both fluid dynamically and technologically.
The experimental characterization of the system is carried out on two different orifice capillary diameters Ø 0.08 mm and Ø 0.1 mm and two different air intake configurations, namely radial and tangential.



2. Comparison between radial and tangential configuration in terms of downstream jet spreading diameter.

By means of an ad hoc developed visual analysis method it is possible to measure the air intake effects in terms of jet spreading and coherence length.
The two air intake configurations, radial and tangential, turned out to produce sensibly different effects on the jet structure: on one hand, by directly impacting on the jet the radial air intake is more aggressive on the jet structure; on the other hand, the tangential air intake has a peripherally "swirl effect" around the jet making the interaction more gentle thus preserving the jet coherence (Figure 2).
Nevertheless, the control of the jet coherence can have effects on the cutting quality since it varies the jet structure interaction with the target

material.
Whereas an experimental campaign tested the enhanced system performances in terms of cutting capability and kerf quality on a real industrial case study concerning closed-cell foams cutting.
Providing cutting energy enough by using the optimal orifice diameter, the radial air intake supplied by high pressure is statistically proved to be the best configuration to be used in cutting applications of soft materials showing an actual improvement of the cut kerf quality by smoothing the striations.
Furthermore, such a system can also be used passively by connecting a pressure transducer and monitoring the process by acquiring the pressure signal coming from the inside of the orifice while working.
Experimental tests showed that the system is able to detect reliably orifice failure rather than the onset of instabilities.
Finally, the air-assisted technology is transferred to high precision abrasive water jet machining integrating it in the design of a μ AWJ cutting prototype.
In this case, experimental trials based again on visual analysis demonstrate that a vacuum-assisted orifice with a tangential configuration is the best choice since it still guarantees the jet



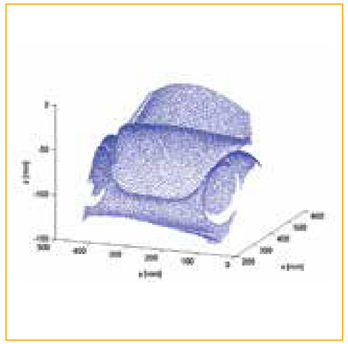
3. Sample gears of different materials and thicknesses cut by the developed μ AWJ system.

stability with a further increase of the jet coherence.
This is crucial when dealing with abrasive micro machining where a perfect control on the process parameters and a reduction of the sources of instability is fundamental.
The vacuum assistance makes the process stable and produces a highly coherent jet, thus allowing the downsizing of the cutting head preserving it from abrasive clogging.
Again, the μ AWJ cutting system is characterized technologically and tested as well on some case studies in order to prove the effectiveness of the solutions (Figure 3). In particular, concerning kerf quality, the tests prove how very good performances are achievable making this technology to compete, on equal footing, with other micro-machining processes.
Water jet could be able to cut considerable thicknesses faster, ensuring high productivity and moreover it is a completely independent material process.
The main purpose for the future is to challenge with other non-conventional technologies such as laser and EDM, in all those industrial areas concerning the machining of metal and nonmetal, heat-sensitive and non-conductive materials, composites and considerably thick workpieces.
Concluding, the Air-Assisted Water Jet technology is a viable way to enhance the process capabilities aiming at an holistic improvement of the Water Jet technology as a whole, opening the way to new applications in the field of high precision and micro machining.

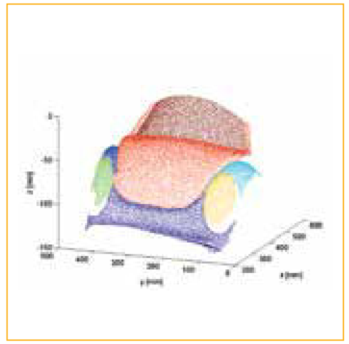
SURFACE RECONSTRUCTION AND MONITORING VIA GAUSSIAN PROCESSES

Paolo Costantino Cicorella - Supervisor: **Quirico Semeraro, Bianca Maria Colosimo**

Over the last years, there has been an increase in global competition, particularly within manufacturing. In this highly competitive scenario, shorter time and reduced costs for reaching the final client have become critical factors for any company involved in product development. The capability of achieving and maintaining a consistently high level of quality, both of the final manufactured good and in the entire design and manufacturing process, is fundamental in achieving such goal.
Modern manufacturing is characterized by low-volume high-variety production and close tolerance high-quality products are required, making quality control and inspection essential methods for measuring and controlling geometric variability.
Geometric tolerances have been gradually introduced alongside traditional dimensional tolerances, with the goal of providing a more comprehensive way for defining allowable variation for a given product geometry. Unfortunately, the time spent for inspection is an important factor that affects the final cost of a product. Hence, advanced measurement technologies, which provide the opportunity to collect thousands of data points in short time, have been developed.
Now, fundamental challenges are related to how to acquire and analyze geometric information more efficiently and effectively in order to cope with the increased requirements.
The key ingredient here is an excellent surface reconstruction algorithm, which allows the reconstruction of a continuous surface given the scanned point samples of an unknown surface. This would be useful for many applications in industrial applications. Engineers can inspect the quality of their manufactured parts by scanning them and comparing with the original CAD model to assess if the feature variation is confined within acceptable boundaries (product quality inspection), or in statistical process monitoring, where it is necessary to capture the item-to-item variation to quickly detect any change in the manufacturing process from its in-control state.
The main purpose of this thesis is to model the "signature" (*i.e.,* systematic pattern) left by the process on the manufactured feature via Gaussian Process models (GPs) with a double goal: *i)* to present two methods for automatic reconstruction of accurate and smooth surface model of arbitrary topological type from unorganized sample points and, *ii)* to develop and analyze a novel statistical monitoring method which uses the GP-predicted deviations of a surface from the in-control pattern.
The first part of the work regards the statistical reconstruction of shapes based on large datasets, which represents the geometry of a part measured by means of a non-contact device. These pose tremendous computational challenges for all statistical methods; for instance, spatial models based on GPs involve inversion of matrices that, for *n* observations, generally requires $O(n^3)$ operations and $O(n^2)$ computational memory, an amount of operations that remains out of reach with classical procedures, even for large clusters of processors.
To overcome this issue, a new method called local GP has been proposed in the literature. It decomposes the entire domain into smaller parts and, to predict the value at a specific location, it uses only the points in the subdomain where the test site belongs to.
Our surface reconstruction is a generalization of the subdivision surface scheme introduced before. A principal contribution of our work is to show how it is possible to modify the classic subdivision rules to model adaptively more general shapes.
In this framework, we proposed a new technique, based on a rotation of the surface followed by a nonparametric statistical technique called CART, which provides fairly comprehensible predictors in situations where many variables interact in nonlinear ways. Besides, it allows to automatically find an adaptive mesh able to effectively adapt to local abrupt changes in the surface. Unfortunately, when the algorithm is applied to very complex shapes composed of multiple freeform surfaces, e.g. car bodies, the resulting partition of the space is characterized by many small regions. To overcome oversegmentation issues, we **adopt** another segmentation procedure, **able to produce results in accordance with cognitive science. E**xperimental results show that our proposed approach can be applied to real-world cases (Figure 1a – 1b), and a comparison with other methods shows that this is more accurate.
The last topic of the reconstruction part regards multisensor data fusion methods. They are used to go one step further by seeking original and different ways to analyze and combine multiple measurement datasets taken from the same measurand, in order to produce synergistic effects and ultimately obtain overall better measurement results.
In the second part of the work, a GP-based approach for surface monitoring is presented and analyzed through an extensive simulation study. Statistical surface monitoring is a new area of statistical process control (SPC), which has its origin in profile monitoring, where the quality of a process is best characterized by a functional relationship of a single variable.
In this case, classical solutions cannot be adopted since it is well known that a sample with huge size usually degrades the detection performance of a multivariate control chart. For this reason, a novel statistical process control based on GPs is proposed, which collects all the point cloud information in few parameters and uses predictions in specific locations as a measure of deviance from the nominal behavior.
This approach is able to detect unwanted changes of the surface, provided that appropriate number and sampling strategy of predicted points to be monitored is considered. In particular, it is proved that an optimal number of locations, where the surface has to be predicted exists, in order to maximize the probability to detect shifts of the process.
The innovative nature of the result is linked to the ability to break free from having to monitor the shape in a fixed number of points, which traditionally coincide with the measured ones, giving the possibility to flexibly choose their position and optimal number, to optimize performance of a quality control procedure.



1. Measured dataset



2. Segmentation result

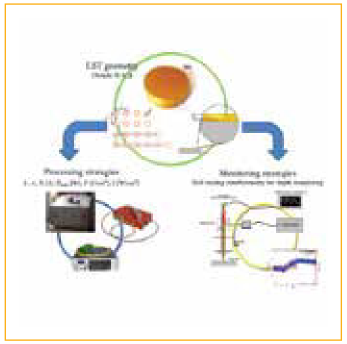
DEVELOPMENT OF PROCESSING AND MONITORING STRATEGIES FOR LASER SURFACE TEXTURING OF TIN COATINGS

Ali Gökhan Demir - Supervisor: **Prof. Barbara Previtali**

Today, the attention on treating surfaces as functional aspect of a component grows, and the ideal of achieving designed or tailored surfaces becomes more relevant. Direct writing with the laser beam is the most flexible among possible manufacturing methods, since the same optical chain can be manipulated to work on different materials and patterns. Laser surface texturing (LST) is an ever growing application field that unites the micro geometries to large areas for functional surfaces. In particular, surface texturing in the form of shallow micro-dimples can improve the tribological behaviour of the component by containing lubricant inside the dimple, entrapping the wear debris, and contributing to the load bearing by generating hydrostatic pressure in the dimple.
LST was developed for cold drawing dies with hard solid ceramic TiN coatings. These components undergo high friction forces, which can generate defects on the die itself or the component realized with it. In the present context, LST is destined to be applied to single or small batch components of high value. The applied TiN coating is 3-5 µm thick and laser machining should be limited in this extent. These components, due to their dimensions, are also difficult to measure or control after process. Bearing in mind the texture dimensions, the control method would be based on high resolution microscopy applied on large surfaces. Such instruments adaptable to form of different dies are not commercially available. This means the process stability is crucial, which emphasizes the need of on machine, in-line measurement capabilities. This fact generates two important points that need to be addressed from research point of view:

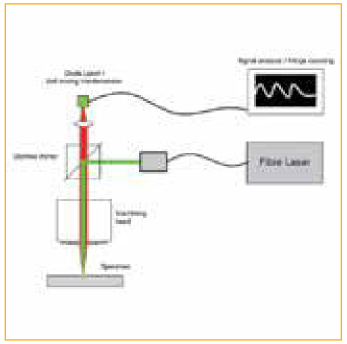
1. As LST requires covering large areas with micro features, it is foremost important that the process should be applied with an industrial tool to render it economically viable to industrial production.
2. A method should be developed to monitor dimple depth, which is the most critical aspect of the laser machining process.

Laser micromachining with industrial fibre lasers and laser self-mixing interferometry were chosen as processing and monitoring methods (see Figure 1).
The present thesis work is mainly based on physical models used to explain the different machining regimes with different laser systems. Three different fibre laser sources installed in Politecnico di Milano and University of Cambridge were employed. Three different TiN



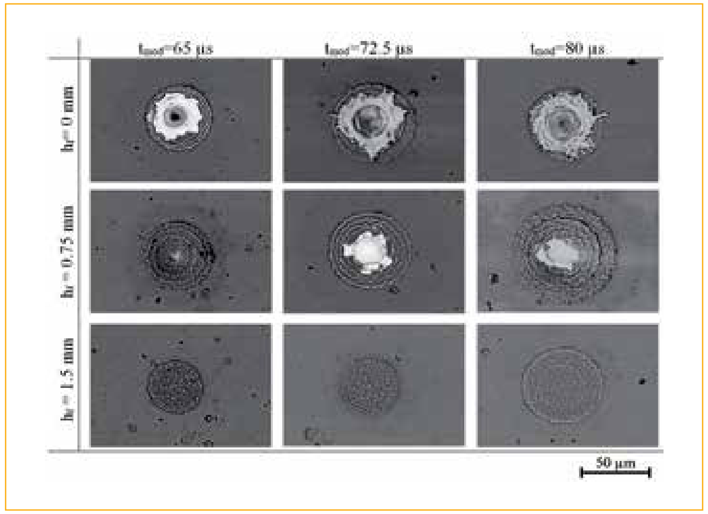
1. The PhD project scheme depicting the two main parts of the work.

coated substrates, representing industrial state of the art in die materials were used. The studied pulse duration range was 1-250 ns, with 1 µm and 0.5 µm wavelengths. Therefore, for each laser source a processing strategy was presented to control dimple diameter and depth, an experimental plan using the chosen strategy was proposed, and the efficacy of the processing strategy was evaluated.
Ablation depth measurement was studied in the scenario of percussion drilling of TiN coating on 39NiCrMo3 substrate with the MOPA, short ns, 0.5 µm fibre laser. The chosen scenario represented the best choice in micromachining quality with high productivity. The aim of the study was to prove the concept and demonstrate the limitation regarding future industrial



2. The scheme of laser self-mixing interferometry for ablation depth monitoring

applications. The measurement scheme used a 785 nm self-mixing interferometer beam launched into the same optical path with the processing beam (see Figure 2). The measurement was based on counting of interference fringes. Each fringe occurs at a displacement of λ/2, which also determines the resolution of the measurement device. The design requirements of the monitoring system and then the solutions incorporated on the realized opto-mechanical system were described. The system was then characterized for operational capabilities, especially in terms of interaction with the process emission and generated plume. The measurement performance was evaluated in comparison to a conventional depth measurement instrument.
The results regarding the laser micromachining performance of ns pulsed fibre lasers have confirmed the feasibility of obtaining high quality dimples on ceramic coatings with accurate control of processing depth. Dimples with diameters between 20-60 µm were achieved without damaging the coating material with the



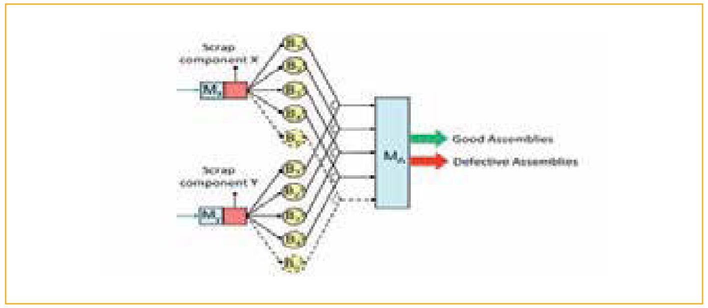
3. SEM images of the dimples on TiN coating obtained with the Q-switched fibre laser with 250 ns pulses.

substrate contamination. When machining beyond the coating thickness, high quality dimples without dross generation was achieved with 1-12 ns pulses. It has been confirmed that the developed processing strategy depends highly on the automation possibilities and the used beam manipulation system. The highly energetic Q-switched system that generated 250 ns pulses was used in a non-conventional manner to obtain pseudo single pulses. Although this approach enabled the feasibility of accurate depth control with the laser, the productivity was reduced compared to less energetic pulse duration variable and long ns MOPA systems. It has been observed that pulse durations around 1-12 ns seem to avoid melt generation, whereas longer pulses improve throughput. Pulse tunability therefore appears as an important feature for the next generation laser sources.
The self-mixing interferometry system with 0.4 µm depth and 29 ns time resolution was designed and implemented for ablation depth monitoring. The use of the system for measuring the displacement of the ablation front was validated in fast ablation conditions with limited machining depth. The critical point in the measurement remains with the fact that the used coherence detection method is prone to disturbances caused by the turbid media around the ablation zone. The problem was resolved by the use of a side gas jet, which is expected to divert the ablation plume and allow the measurement beam to pass into the drilled microhole. The self-mixing measurement was found to be statistically same to the ones carried out with the conventional measurement system.

INTEGRATED QUALITY AND PRODUCTION LOGISTIC PERFORMANCE MODELING FOR SELECTIVE AND ADAPTIVE ASSEMBLY SYSTEMS

Dariush Ebrahimi Azarbayejan - Supervisor: **Prof. Marcello Colledani**

Managing quality in the current turbulent manufacturing environment becomes crucial as the customer's requirements increase while companies are under cost pressure. Quality becomes even more critical when manufacturing systems join components. Typically, reducing the components' production variability is considered as an approach to improve the quality of assembled products, although increasing manufacturing time and cost. This approach can be infeasible, since the possibility of processing the components with lower variation is limited due to inherent process capability constraints.
Selective and Adaptive Assembly Systems are considered as a functional built method to improve the quality of the assembled product. The selective part of Selective and Adaptive Assembly Systems is characterized by the assembly of components based on matching predetermined classification groups. The adaptive part of Selective and Adaptive Assembly Systems is characterized by the control of process parameters in the upstream component manufacturing processes to produce components for a specific quality class. Parts are treated as individuals rather than statistically identical members of an ensemble. This is usually expensive but it is used when the alternative, namely making the parts accurately enough for interchangeability, is even more expensive.
Selective and Adaptive Assembly Systems is applied in traditional industries such as mechanical component assembly.. In fact, due to the increasing pressure on high precision manufacturing and to the development of advanced and fast measurement technologies supporting on-line applications, selective assembly systems have attracted increasing interest in the last five years. Recently, selective assembly is applied in fast growing sectors such as micro-production, in renewable energy equipment production, and in the automotive body assembly.
Several studies investigate the performance evaluation of Selective and Adaptive Assembly Systems from quality point of view. They typically consider the problem only from a quality perspective and neglect important production logistics features of the system, such as finite capacity buffers and unreliable machines. However, the complexity of logistics system in Selective and Adaptive Assembly Systems deteriorates the system productivity.
The most important innovation of this thesis is the development of ***an Integrated Quality and Production Logistics Model for the Design of Selective and Adaptive Assembly Systems***. It is often necessary to evaluate many alternative system configurations in a short time which is only possible to perform with analytical methods.
Therefore, a completely new analytical method is developed to estimate the system performance of Selective and Adaptive Assembly Systems.
In addition we have developed several ***efficient deadlock avoidance policies*** because the policies which are proposed in the literature results in high level of scrap as well as system logistic complexity.
Although in the literature the process adaptation design is addressed profoundly, but ***optimally designing the process adaptability*** in Selective and Adaptive Assembly Systems is not considered. Therefore, additional contribution of this thesis is a method to derive the optimal parameters of process mean shifts to meet desired levels of components matching.
An example of selective assembly system is represented in Figure 1. This system can be integrated into a longer process-chain. We specifically focused on the integrated quality and production logistics performance of the selective assembly cell. We considered a selective assembly system where



1. Schematic representation of Selective Assembly Systems.

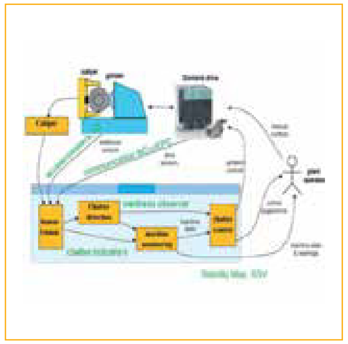
two sub-assemblies, namely x and y, are assembled. The sub-assemblies are respectively processed by machines M_x and M_y. After the process, each component is inspected and sorted into buffers, according to the measured key quality characteristic value.
Firstly, in order to achieve the performance of the system through above mentioned model, for each sorting machine as well as assembly machine a specific homogenous discrete time-discrete state Markov chain, has been characterized. In fact, for each machine the Markov chain separately includes all the machine states. (This is called Machine Level Decomposition). Then, a buffer level decomposition (BLD) for each buffer downstream of splitting machines is structured, i.e. a building block for each buffer that evaluates performance of that specific flow.
Therefore, an analytical iterative algorithm between machine level decomposition and buffer level decomposition is developed in order to compute Markovian states probabilities in steady state which is used to evaluate an approximate overall system performance. The analytical performance evaluation model is developed and implemented in C++. The developed tool is tested in terms of accuracy and precision by discrete event simulation models.
The developed analytical method is applied to observe the system behavior of the selective assembly systems when the total buffer space is increased. The results show that although the selective assembly system provides a higher system yield with respect to the non-selective assembly system, but it affects negatively the total throughput of the system. It is shown that the total throughput of the system increased as the total buffer space increases, but due to the logistic complexity of the selective assembly system the total throughput of this system is reduced compared to the non-selective assembly system. It is important to notice that the negative effect of selective assembly system on the total throughput become less evident as the total buffer space increases. The combined result of increased yield and decreased total throughput is the remarkable increase of the effective throughput with respect to the traditional, non-selective, assembly system. In addition, the positive effect of the selective assembly system on the effective throughput of the system is even more visible as the total buffer size increases. The behavior of the selective assembly system under more quality classes is explored and the results of the simulation show that although the total throughput is reduced, the system yield is increased as the number of quality classes increases. As a result of this competing effect, the effective throughput curve is concave. Thus, being concerned with the concave behavior of the effective throughput curve, it illustrates that there is an optimal point to select for the number of quality classes. Therefore, in order to make a proper decision for design of selective assembly systems in terms of number of quality classes, there is an absolute need to observe the trade-off between the total throughput and the system yield through the resulting effective throughput.

MODEL-BASED MONITORING AND CONTROL OF MACHINE TOOLS DYNAMICAL BEHAVIOR TO ENHANCE MACHINING PERFORMANCE

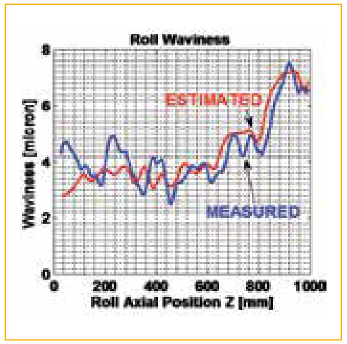
Paolo Parenti - Supervisor: **Michele Monno, Giacomo Bianchi**

Machine dynamic is a great important issue in modern manufacturing, especially for machining systems, because of its direct effects on part accuracy, surface quality/integrity, tools and machine components wear/breakage and lastly on energy consumption. The work presents the development of different monitoring and control tools that help coping with dynamic problems affecting machine tools and cutting processes, by means of model-based approaches.

Part A – Grinding: Major attention is given to cutting instability phenomenon in roll grinding and the related surface waviness formation. The study of this topic is framed in a research project that involves one of the top world-leading manufacturer of roll grinding machines. Chatter is one of the critical aspects that must be taken into account since it hinders the surface quality and the geometrical accuracy of the ground workpiece, which are the main goal of this process. Therefore, Automatic Chatter Detection becomes fundamental for supporting grinding operators in performing chatter-free operations and mitigate the negative effects associated with this phenomenon. Technological synthetic indicators for grinding



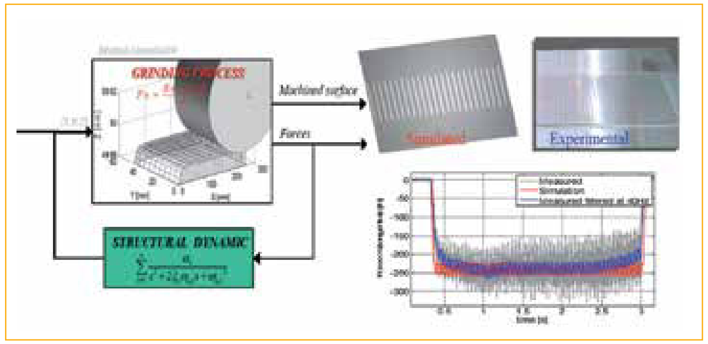
1. Architecture of the developed process controller



2. Waviness Observer online estimation compared with offline direct measurements of the roll waviness

chatter monitoring have been developed for this purpose, basing on a sensor fusion approach of accelerometers and NC drives data. Automatic Chatter Control represents an additional step ahead toward the achievements of good system performance. Most of all the existing solutions in literature requires strong modifications of the system setup and the use of additional expensive sensors, which often are not suitable for an easy industrial exploitation. In this work a model-based Automatic Chatter Control architecture for waviness avoidance, that is compliant with the constraints imposed by the industrial application, is proposed (Figure 1).
The controller works in closed-loop using a waviness observer module as feedback and the process parameters, such as the workpiece and the grinding wheel speed, as control variables. Stability theory of the grinding process is exploited for supporting the decision actions which consists in the application of speed tuning or continuous speed variation strategies. The waviness observer module is aimed at identifying the surface defects online (during the grinding process) basing on the forced response of the machine structure to force perturbations. The closed loop dynamic behavior of the machine and process is described by models of the open loop system and the linearized grinding process. Thanks to the closed-loop response function, it is possible to extract and quantify the only contributes related with waviness, from the acceleration

response of the structure (Figure 2), supporting the activation of the most proper control action. The control architecture has been implemented in Labview® and deployed on a National Instrument real-time control platform. The solution, tested on a specifically equipped grinder has demonstrated to reduce significantly the negative effects associated with the dynamic interaction between machine tool and chipping process.
All the above analyses have taken advantage of a comprehensive time-domain grinding simulation model, used as a reference virtual machine, which has been developed during the PhD work, in collaboration with ITIA-CNR. The model relies on a tridimensional discretization by means of a Z-buffer approach and it is able to provide static and dynamic grinding force components by taking into considerations all the relevant aspects, such as cutting force non-linearities, contact stiffness, process damping and generalized machine dynamics with multiple degrees of freedom (Figure 3). Non-linear grinding wheel wear behavior is under study and will be object of future development. Validation tests has been carried out on a surface grinding machine confirming the good performance of the model.



3. Time-Domain Simulation model of Grinding Process

Part B - Milling: Minor investigations have been devoted to the study of the dynamic behavior of milling process and milling machines. A real-time monitoring module aimed at identifying the onset of regenerative chatter in milling operations and estimate the chatter frequency in real-time is proposed. The approach, based on recursive fitting of a cutting forces model is presented along with simulated and experimental applications that exploit accelerometers, dynamometers and microphones. In general, reducing cutting forces decrease the tendency of the cutting system to develop chatter.
The idea is to adopt Ultrasonic Vibration Assisted Machining (UVAM) technique in this regard. A preliminary experimental assessment has been carried out for the micro-milling case to evaluate the actual force reduction allowed by UVAM. Future studies will be devoted to the coupled effect on cutting stability. Another investigation has been focused on inertial vibration affecting multi-axis milling centers. A feasibility analysis for compensating the dynamic compliance through the application of a model-based feed-forward approach has been carried out. The possibility to use feedback control has also been discussed confirming that both solutions can be adopted on real systems. Surface defects, associated with the structural inertial deformation, can then be actively reduced.