DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Bianca M. Colosimo

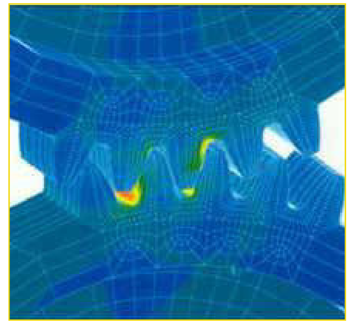
Mechanics is one of the leading and driving sectors of industrial manufacturing in Italy. Our country features one of the strongest economies by GDP, being ranked 8^{th} on a worldwide scale (International Monetary Fund, 2011). In terms of per-capita manufacturing production, Italy holds a strong 4^{th} position in the world, and ranks 2^{nd} in Europe (Confindustria, 2010).

In this competitive scenario, and in order to respond to the requests of a challenging sector, our PhD Program, organized within the Department of Mechanics, aims at providing PhD candidates with specific training in Mechanical Engineering by strengthening their research and problem-solving abilities in industrial and academic contexts.

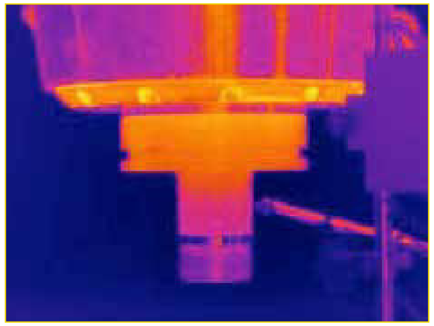
In particular, we emphasize issues of continuous improvement of interdisciplinary education and integration of procedures, ranging from conception to realization. A PhD candidate in Mechanical Engineering follows a path that includes studying activities, research, lab experience, active cooperation with industries, foreign institutions and international research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with practical industrial problems. In this view, their scientific profiles are suitable for prestigious positions at national and international level within industrial companies, consulting companies, universities and research institutions. Our Program numbers about 30 candidates per year.

RESEARCH AREAS

The PhD Program in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas:
Dynamics and vibration of mechanical systems and vehicles: this research line is organized into five research areas, namely Mechatronics and Robotics, Rotordynamics, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It covers modelling of linear and non-linear dynamic systems, stability and self excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.
Measurements and experimental Techniques: the Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques as well as in the customisation and application of well-known measurement principles in innovative fields. The MTM research focuses are the design, development and metrological characterisation of measurement



systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.
Machine and vehicle design: this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibres), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. The optimal design and the testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.
Manufacturing and Production Systems: this research field gives relevance to the problem of optimal transformation of raw materials into final products addressing all the issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life cycle. Ph.D. activities can specifically focus on one of the following research fields: Manufacturing Processes (MPR); Manufacturing Systems and Quality (MSQ).
Materials: this area is focused on the study of production process and characterization of materials for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design ecc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed the activities on three main research topics such as Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.
Methods and Tools for Product Design: research in this field is organized in two main research topics, PLM-Product Lifecycle Management, that includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping that includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.



LABORATORIES

One of the key elements of our Doctoral Program is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: Cable Dynamics, Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Dynamic Testing, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

INTERNATIONALIZATION

We foster internationalization through the support of PhD candidates' mobility for research periods abroad, and we have experienced a growing trend of foreign students enrollment over the last few years. We encourage Joint Curricula with foreign universities and Double PhD Programs; we organize every year PhD courses delivered by foreign professor. The Program is widely active in supporting and promoting international networks and joint teaching programs with prestigious institutions all over the world, holding a strong tradition of academic cooperation and agreements with some of the highest level and best known universities such as MIT, University of California at Berkeley, Imperial College, Delft University of Technology, Technical University of Denmark, Pennsylvania State University, University of Bristol, Technische Universität Darmstadt, University of Bristol, University of Sheffield, Fraunhofer Institut LBF Darmstadt, Universidad Politécnica de Madrid, Tokyo Polytechnic University, Universidad de Concepcion, University of Miami, the University of Western Ontario.

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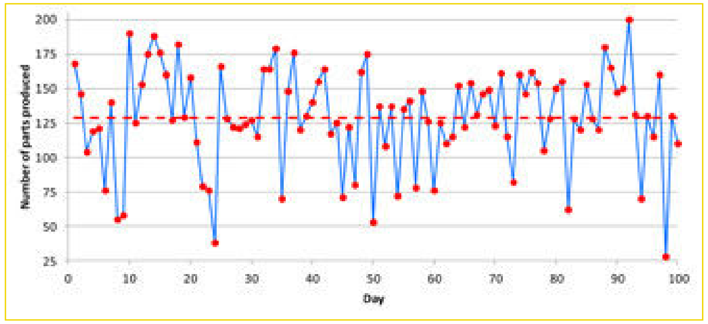
ANALYSIS OF THE OUTPUT VARIABILITY IN MULTI-STAGE MANUFACTURING SYSTEMS

Ramiz Assaf

Manufacturing systems nowadays are designed, evaluated, reconfigured and optimized based on their average performances, such as the average production rate denoted E or average work in process... etc. Although this practice is reasonable for the long term evaluation of the Manufacturing system, industrial evidence shows it is not suitable for the short term evaluation. In fact, the observed daily cumulative output of any manufacturing system can be very different from its average. Figure (1) depicts a time series plot of the daily number of produced parts and the long term average (dashed line) for a studied manufacturing system that has 23 machines and a total of 144 different failure modes, the coefficient of variation for the output of this system is 0.264.

A manufacturing system is composed from a set of machines. Each machine has a lot of interacting components and mechanisms that are prone to failures. Machine failures happen randomly and the time needed to repair a failure is not deterministic. This repeated failure-repair phenomenon is the main source of the variability in the output of the manufacturing system and cause the observed short term behavior to be different than average one.



1. Time series plot of the daily production for a studied company

If output variability is not considered in the design or the evaluation phases of the production system, it will often give a misleading picture of the system's short-term capacity. This could create different problems like; making sub-optimal decisions, being unable to satisfy the demand contracts, regular need for overtime...etc, all these situations are translated directly into extra costs.

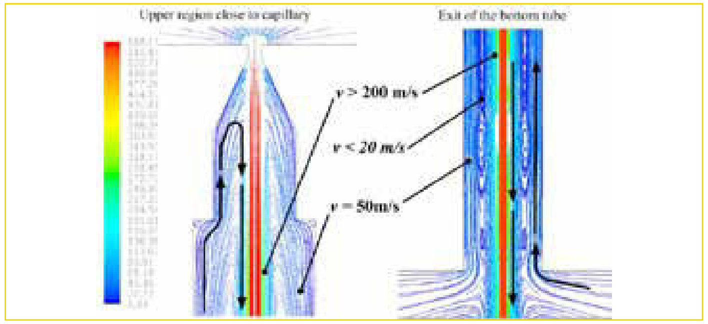
Pioneer works in the field on output variability evaluation, proposed the output asymptotic variance rate denoted V, as a releDvaynt performance measure. The output asymptotic variance rate is defined as the limit of the variance of the output process per unit time, as time approaches infinity. This performance measure can be used as a machine parameter to compare different machines during system design phase. Moreover, it can be also used with the average production rate to calculate the service level of the manufacturing system.

The gap in the literature is wide; the number of papers discussing this problem is few. Most of the works introduced use simple machine models that fail to capture the complexity of calculating V. Other works do not consider failure modes and considers variable processing time. Finally most of the works can only be applied to manufacturing systems with a small number of machines and buffer capacities. The proposed research aims at providing methods to estimate V in multi-stage manufacturing systems with finite buffers and complex machine structure using approximate analytical methods. The first part of the work is focused exact analytical evaluation of the output variability for machines modeled with general Markovian structure, and developing efficient and precise algorithms for the calculation. The exact analytical evaluation allows understanding the behavior of V as a function of the machine parameters. This is also extended to two machine one buffer system, focusing on the effect of the buffer capacity on V. Furthermore, the reversibility of V in two and three machine lines was studied and numerically proven. Reversibility means that V does not change when reversing the direction of material flow in the system. The reminder of the work is focused on the evaluation of V for multi-stage manufacturing lines using approximate analytical methods namely, decomposition and aggregation. The first approach uses the traditional decomposition method. The manufacturing system is decomposed into two machine one buffer subsystems named building blocks. The idea of this method is to create building blocks that conserve the flow of material throughout the system, thus each building block mimics the behavior of the manufacturing system. Then V is calculated from the last building block using the developed exact analytical method. Using an experimental design the results of this method was compared to the results of a discrete event simulation (DES) model. This method gives very high accuracy for the calculation of the throughput (errors around 0.46%). However, the accuracy of the method for calculating V turns out to be low (about 34%). A modification to this approach is to consider a "three machines two buffer system" as the last building block. This will result in very low errors in calculating E and V, errors are about 1% and -5.25% respectively. However the modified approach becomes very slow in general and only useful when the last two buffers have small capacities. The second approach developed for the calculation of V for multistage manufacturing lines uses the idea of machine aggregation. The method takes the first two machines-one buffer system of the multi-stage manufacturing system, and then it calculates E and V analytically and transfers the two machine-one buffer subsystem into a pseudo geometric machine with single failure mode. Afterwards, using the pseudo machine and the following buffer and machine, the new subsystem is constructed and evaluated. This process is repeated until the end of the manufacturing system. This method reduced the error in calculating V to 8%. However it suffers low accuracy for the calculation of E as it does not iterate throughout the line. Finally, this method is the fastest among all developed methods in this thesis.The third approach is a decomposition approach that makes advantage of the reversibility property in the two machine manufacturing systems. The decomposition is done with new equations that match V throughout the system, by adding a new geometrically distributed failure mode. Results were very accurate 0.59% and -5% for E and V respectively. The only problem found in this approach when V cannot be matched with a geometric distribution, we obtain invalid results. This issue is solved algorithmically by setting some constraints on the parameters found, this will guarantee a solution with an additional error. Errors in this case increase to -1% and -11% in E and V respectively. This method is fast too, it can solve a system of 10 machines within one minute. Based on the developed analytical methods, a new approach for the optimization of manufacturing systems has been proposed. The new approach aims at providing the optimal configuration of the buffers by maximizing the service level that jointly considers average and variability performance measures in the optimization problem. The proposed approach was used for the analysis of an industrial case, that has a buffered multi-stage manufacturing system. The new optimization approach shows different results than other approaches that do not consider the output variability. Finally we give guidelines for practitioners and production managers to deal and reduce the output variability in their manufacturing systems.

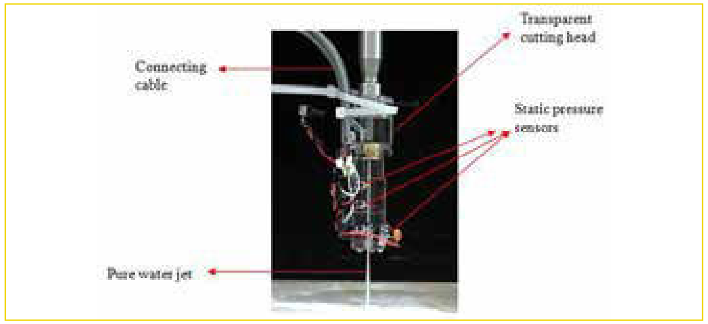
HYDRODYNAMIC STUDY OF FLOWS INSIDE ABRASIVE WATER JET CUTTING HEAD

Amanuel Tesgera Basha (Manufacturing and Production Systems)

Abrasive water jet (AWJ) makes use of a high velocity slurry jet, while in the pure water jet (PWJ) the high velocity water jet emerging from an orifice is used as a cutting tool. Inside the cutting head, there is a large-scale of turbulence mixing and momentum transfer that takes place. This results in a situation where the jet exiting the cutting head acts as the cutting tool eroding the material without heating, thus, a cold cutting process.
AWJ cutting has passed through great stride over the past 30 years. The developments have succeeded in bringing the technology to a rival with other cutting technologies such as laser cutting and plasma cutting in such a short time. This challenge is continual as the potential of this process is continued to be exploited. Yet, process conditions (jet characteristics) are still unpredictable to a large extent and this impedes a difficulty in the development. These bases on the insufficient knowledge of the associated characteristics of a cutting head operation and absence of the comprehensive understanding of its flow characteristics.
Consequently, a certain driving motivation arouses on the study of the existing cutting heads before developing new systems and accordingly advances in the research. The present work is focused on the study of the cutting head flows associated with the idea of creating tools to develop the research on cutting head flows by studying the three phase flow phenomena by numerical and experimental methodology.
The analysis in the thesis work starts with a conceptual review of the abrasive water jet cutting head from different aspects.
A detailed component based analysis of the cutting head is a subject of the thesis.
In the first part of the study, the flow through water jet orifices was studied. Its study was important to understand the effect of the internal geometries of orifices on the jet characteristics. In this study, Computational Fluid Dynamics (CFD) simulation was performed to improve the understanding of water jet formation and fluid flow process through the orifice under high injection pressures.
In particular, water jet formation and reattachment length in sharp edged diamond orifices were studied. The investigation used a two dimensional, axisimetric, two-phase, transient-state model of orifice flow to observe the effects of capillary length and diameter on the jet break-up length. The injection pressure was varied from 10 MPa to 700 MPa. Results are presented for two standard diamond orifice types.
In the second part of the study, jet stability and effect of droplets collisions inside an orifice where studied. The internal geometry of the orifice plays an important role during the first instants of the jet creation affecting the jet break-up and the creation of droplets which remain inside the orifice sticking or rebounding on the walls of the orifice exit tube.
A CFD analysis is carried out to study the effect of the droplet collision with the main jet: the jet break-up, early presence of water, condensed humidity or jet disturbances can create these water droplets which then can be dragged by the high velocity air field created inside the orifice tube by the main water jet (Figure 1). Droplets can later collide along the main jet or be sucked up towards the capillary (the upper small orifice hole where the jet is created) causing local disturbances and loss of the hydraulic flip condition which is crucial for the coherence of the jet. This random process effectively explains the instabilities which can usually be noticed by a naked-eye observation during the water jet formation and later on; the study of this phenomenon can lead to new instruments for an improved design of water jet cutting head components on the way to high precision applications. The results of simulations are validated by means of a high-speed camera.



1. Path lines of air inside orifice tube colored by velocity magnitude [m/s].



2. Sensorized transparent cutting head.

The third part of the study deals with, the effect of water jet orifice housing geometry downstream of the orifice on the stability of a pure water jet. It is presented with a view to enhance the performance of contour cutting of foam materials in the seals and gaskets industry. CFD analysis is performed and it is found that the velocity magnitude and coherence of the jet is dependent on the geometry of orifice housing. The CFD results are compared with imaging experiments and previous work obtaining good agreement. A factorial experimental work is then developed. The results show that the geometry of orifice housing plays an important role in the accurate contour cutting of the foam material.
The last part is dedicated to the discussion of the detail of flows in side abrasive water jet cutting heads. Cutting heads are critical components affecting the cutting performance of abrasive water jet (AWJ) technology. Therefore, investigating their characteristics to achieve efficient design is fundamental to improve this technology. In this study, Computational fluid dynamics (CFD) models for ultrahigh velocity water jets and abrasive water jets (AWJs) are established using ANSYS FLUENT software. Jet flow dynamic characteristics inside a cutting head are simulated under unsteady state, turbulent, two-phase and three-phase flow conditions. Water and particle velocities in a jet are obtained under different operating conditions to provide an insight into the jet characteristics and study the effect of cutting head geometry. The comparison with own experimental (Figure 2) data shows the accuracy of the numerical simulations in predicting cutting head performance, as well as revealing the effect of operating conditions. Besides, it is found that the flow pattern does not depend much on the position of the abrasive and air suction zone. This investigation aids the understanding of the flow inside AWJ cutting head and provides information for designing these components to suit optimum performances. Consequent CFD results include detailed flow profiling through path line tools, pressure and velocity evolution.

STATISTICAL MONITORING OF VERTICAL DENSITY PROFILES

Marcela Meneses Guzma (Manufacturing and Production Systems)

The main objective of this thesis is to investigate new routes to statistical monitoring of complex profiles.
Statistical process monitoring (SPC) is aimed at detecting deteriorated process performances. Traditionally, this task is achieved by measuring some quality characteristics of the process output which are assumed to be modeled as an univariate or multivariate random vectors. Instead, there is an emerging field of interest in the profile monitoring literature, where it is assumed that the process or product quality can not be simply modeled as a random variable but it is instead related to a profile (or functional data) or to a surface. A profile is a function which relates a response to one or more location variables. Consider, for examples the density of a profile as a function of depth, signals from machines sensor, profiles connected to geometric characteristics (straightness, roundness, etc.). In these cases a control strategy should be able to signal rapidly with an alarm if the profile is different from the in-control profile. Profile monitoring consists in combining approaches for functional data modeling (as regression) to control charting.

A real case dealing with Vertical Density Profile (VDP) is considered throughout the thesis as reference test case. The shape of this profile significantly affects the properties of particleboard panels produced in the wood composite manufacturing industries. Fig. 1 shows a typical VDP pattern (blue line or in-control VDP), where the density (kg/m^3) on the y axis is reported as a function of the vertical location x at which it is measured. Fig. 1 also shows an example of out-of-control VDP profile, which should be quickly detected by the quality control procedure.

In this thesis, two different profile monitoring procedures fir complex profile monitoring are developed and investigated. The first approach is based on a parametric model of the profile (S+ARMA) combining spline regression with autocorrelated errors for a profile j,

$$\boldsymbol{y}_j = s_j(\boldsymbol{x}) + \boldsymbol{v}_j \qquad j = 1,2,\dots,J$$

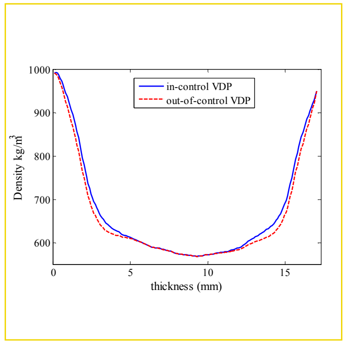
where $s_j(x)=\sum_{k=1}^{r} c_k B_{k,i}(\tau;x)$, $B_{k,i}(\tau;x)$ is the B-spline evaluated in x with knot vector τ, c_k are the control point of the curve and r the number of model parameters. The vector $v_j=v_{1j},\dots v_{tj},\dots v_{nj}^T$ represents the autocorrelated errors observed for the jth profile. These monitoring procedure supposes that is more efficient to summarize the in-control performance with a parametric model and monitor for shifts in the model parameters. We use a multivariate control charts to monitor the coefficients of the model and a univariate control chart to monitor the error standard deviation with time.

The second approach is based on nonparametric mixed-effects models (NPME) which assume the form

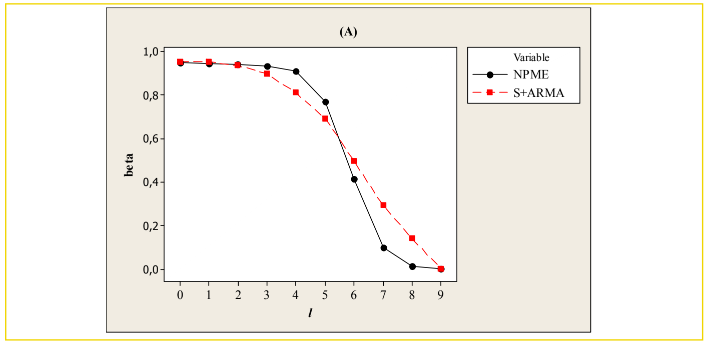
$$\boldsymbol{y}_j = g(\boldsymbol{x}) + f_j(\boldsymbol{x}) + \boldsymbol{\varepsilon}_j,\ j = 1,\dots J$$

where y_j is the processes response and x the design point for the profile j; $g(x)$ models the overall pattern that characterizes all the profiles and $f_j(x)$ represents the individual curve deviation from $g(x)$ and is called the random-effects curve. This monitoring procedure uses a multivariate control chart based on the deviation between the model predicted data points and the observed ones ($f_j(x)$), and a univariate control chart to monitor the error standard deviation with time.

Performance of the two proposed procedures are compared considering the time to detect out-of-control states as performance indicator. In order to simulate out-of-control states, we produced 5 realistic scenarios (scenarios A, B, C, D and E) with Eq. 1. Starting



1. In-control and out-of-control VDP.



2. Probability of type II error for the S+ARMA and NPME monitoring approaches for scenario A.

from the in-control values of parameters $c_{1j},\dots c_{10j},a_{1j}\dots a_{4j}^T$, σ_j (error standard deviation of the profile j), we opportunely perturbed these values to introduce changes in the general pattern or in the autocorrelation structure of the profiles. We linked the profile changes to one or more special cause(s) which can cause these conditions.

For example, in the first scenario (A) the drop in the density between the surface layers and the middle layer is increased, the coefficients c_2, c_3, c_8, c_9 change in (-1, -2, -2, -1). This situation may be observed in the manufacturing process when high temperature in the central area of the press is present or low speed pressing is performed. As a consequence, the surface soundness (the degree of cohesion between surface layers and core layers) is decreasing (Fig. 1).

For the procedures performance, Fig. 2 shows the resulting Operating Characteristic (OC) curve for scenario A, where the abscissa l is related with the size of the shift while the ordinate is showing the probability of not detecting the profile change (second type error). The results shows that the parametric method (S+ARMA) outperforms the nonparametric one (NPME) for small shifts. Conclusions are reversed as the shift size increases.

The main conclusions of the thesis are:

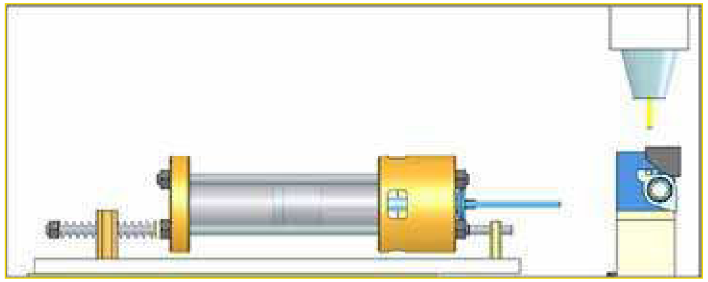
- The parametric approach provides an accurate, flexible and interpretable model for representing functional data by taking the autocorrelation structure into account. Once number and position of the knots are defined, a substantial advantage is that it is easy to implement and computationally fast in the monitoring phase.

- The nonparametric regression technique denotes a great flexibility in modeling the response, since no definition of specific functional form is required. Moreover, it takes naturally into account the correlation structure of the data. However, a realistic limitation to the application of this nonparametric technique is that such a model has not a specific functional form and has no model parameters to estimate. Also, this method is computationally intensive.
- With respect to performance (time to detect a profile change) we conclude that it is difficult to choose a particular method for monitoring VDPs because both the parametric and nonparametric monitoring methods detect out-of-control states and have satisfactory performances. The preference for one approach or the other depends on the type of shift (shift in the curve or change in the correlation structure) or on the shift size.

DESIGN AND CHARACTERIZATION OF A NEW QUICK-STOP DEVICE FOR MICROMACHINING

Lara Rebaioli

Among the available micromachining processes, chip removal is well appreciated for its versatility in terms of workpiece material and geometry, which has led it to be widely used to produce parts for several industrial fields (mechanics, fluidics, electronics, optics, biotechnology, etc…).
However, basic research is still needed to investigate the tool-material interaction and the chip formation at the microscale since several typical phenomena (e.g. the "minimum chip thickness effect", the "size effect", the influence of the material microstructure, the presence of a stable built-up edge, etc…) take place when performing chip removal with small uncut chip thickness and the process cannot be effectively described simply downscaling the existing macroscale models.
The best way to carry out this kind of study is to exploit the so-called "frozen cut" experiments, which allow to "freeze" the chip formation in its steady condition by abruptly stop the cutting action. Hence, the main aim of the present work is to design a new quick-stop device (QSD) to carry out those experiments within the typical microscale cutting requirements (i.e. cutting speed lower than 200 m/min and uncut chip thickness between less than 1 μm and 100 μm); the new device should also



1. Layout of the micro QSD [on the right: tool holder block, on the left: percussion system].

overcome the drawbacks of the existing QSDs (developed in past years for studying chip formation in the macroscale), have a good repeatability and fulfil safety rules.

The so called "micro QSD" described in the present study has been especially designed to be mounted on the Kern EVO 5-axis machining centre available at the "MI_crolab" within the Manufacturing and Production System laboratory of Department of Mechanics of Politecnico di Milano, in order to exploit its high precision (nominal positioning tolerance = ± 1 μm, precision on the workpiece = ± 2 μm) to properly investigate the chip formation in the microscale. A turning operation, which best approximates orthogonal cutting conditions, is performed on the employed machining centre. This operation can be done thanks to a thin-walled tubular workpiece (diameter = 11 mm, wall thickness = 0.5 mm) mounted on the spindle and a tool holder placed on the machine table. The designed layout implies that the cutting action cannot be interrupted by stopping the workpiece or moving it apart from the tool (otherwise forces could damage the machine spindle) but the interruption should be done by abruptly moving the tool. In order to allow the device to reach high accelerations while moving the tool apart from the workpiece and, in the meantime, to fulfill the safety rules, it has been decided to make the tool holder move by means of an impulsive load applied by a striker powered by the energy of pressurized air.
The final micro QSD layout (shown in Fig. 1 and 2) includes a tool holder block (A in Fig. 2), which is fixed to the machine table through a resin block in order to damp vibrations arising from the striker impact, and a percussion system (B in Fig. 2), which is mounted on the machine rigid frame by means of an aluminum support in order to avoid transmission of forces.
Some preliminary quick-stop experiments have been performed to prove the micro QSD effectiveness and repeatability. Fig. 3 shows a micrograph obtained within this experimental campaign in the following conditions: workpiece material: C10 steel, tool material = HSS, α (clearance angle) = 9°, γ (rake angle)= 9°; *f* (feed) = t_c (uncut chip thickness)= 0.05 mm/rev, a_p (depth of cut) = 0.5 mm, V_c (cutting speed) = 50 m/min.

2. Overview of the micro QSD placed in the Kern EVO machining centre [A = tool holder block, B = percussion system] .

3. Preliminary quick-stop test result.

The developed device has to be characterized in terms of performance in order to validate each quick-stop test by means of proper indexes (such as the "separation time" t_s, which is the time the tool-workpiece relative speed needs to become equal to zero, and the "separation distance" d_s which is defined as the distance the workpiece covers relatively to the tool during the tool-material separation process); *ad hoc* sensors and analysis procedures have been designed in the present work in order to fully characterize the QSD in terms of performance. Experimental results show that the quick-stop device fits the design specifics and that each frozen cut test can be validated by means of online measurements.
Since the micro QSD has been characterized, it is possible to use it for improving the knowledge of chip formation in the microscale. This can be done by carrying out experimental campaigns with the aim of studying the effect of several parameters (e.g. tool material, tool geometry, tool coating, lubrication conditions, cutting parameters, etc…) on some cutting process output, such as cutting forces, roughness and built-up edge. This way, the proposed device can be an invaluable support to confirm the statements resulting from analytical or numerical modelling of chip removal process in the microscale; moreover, as concerning practical applications, quick-stop experiments can be exploited by industries for improving tools or process productivity.

STUDY OF A NEW CLADDING HEAD FOR ACTIVE FIBER LASER CLADDING PROCESSES

Bruno Valsecchi

Problem Context

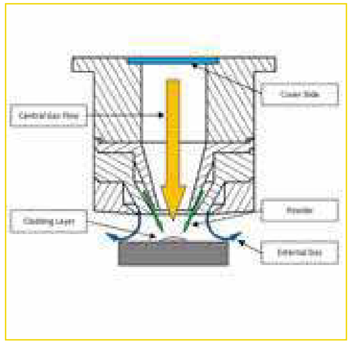
Nowadays the laser cladding process is one of the most complex processes in the industrial laser field. In order to realize a good cladding layer, the control of numerous elements is required, ***i.e.*** the laser source, the process gases, the monitoring devices and the powder. All of these elements converge in the laser cladding head, which is the core of the system. The laser cladding head has to manage all the previous elements in order to realize the cladding layer. Therefore, the laser cladding head has to be opportunely designed. Nowadays several technical solutions are present at a valid industrial level in the case of standard laser sources such as CO_2 or Nd:YAG lasers. On the contrary very few heads are known in the case of the more recent active fiber laser sources. As a consequence the peculiarities of this new laser sources are not completely exploited when the laser cladding process has to be performed.

Aim of the Work

The aim of this work is the study, the design and the realization of a new active fiber laser cladding head with an integrated monitoring system of the cover slide. Firstly the cladding head prototype has to emphasize and exploit the peculiarities of the active fiber laser sources. Moreover the monitoring system of the cover slide has to ensure a continuous check of the status of this device in order to avoid unexpected failures.

The Laser Cladding Head Prototype

The new cladding head can manage three gases by a coaxial architecture realized with different cones shearing the same axis, where each chamber and the relative gas have specific aims. The inner (central one) and the outer gases (external one) are specifically designed in order to match two well known characteristics of the high brilliance active fiber laser sources: the intense heating load on the optical elements of the head and the small diameter as well as the small divergence of the fiber beam. The value of the inner gas pressure represents the best compromise between high values, that ensure an intense cooling effect, and low values, that ensure a calm and gentle interaction of the gas with the molten pool. The outer gas, in addition to the shielding action of the work area, contributes to focus the powder cone onto the laser beam. Thus the powder cone adheres to the laser beam that has a small diameter and low divergence. As a result most of the powder

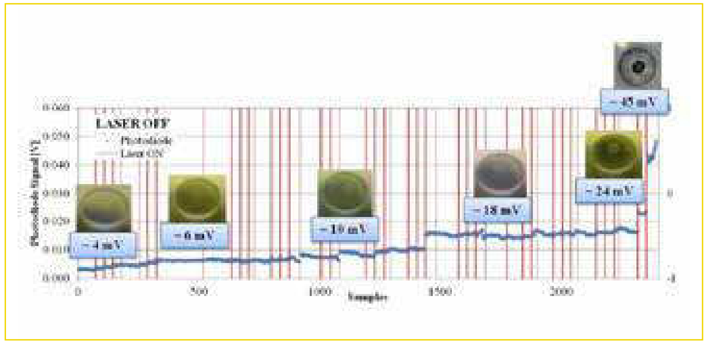


1. Process gas scheme in the new laser cladding head.

comes into the molten pool and the waste of powder is avoided. The last process gas is the powder delivering one. This gas is positioned shortly after the central one. The powder gas has the aim to deliver the powder from the feeder device to the molten pool by means of a bed fluid. A gas channel head scheme is shown in Figure 1. After its realization, the new cladding head has been validated by the analysis of a difficult case study: the cladding of a rotative cutting blade performed with high content carbide powder.

The Cover Slide Monitoring System

This device is specifically designed for high power active fiber laser beams. The available high power density that can be focused on the workpiece surface, one of the most well



2. Example of a monitoring graph associated to a whole cover slide life.

3. Developed new cladding head on the left and a detail of the cladding nozzle on the right.

known positive features of the active fiber laser sources, has inevitably a side effect. This extremely focused heat source is a very critical thermal load acting on the optical elements of the laser cladding head, in particular in dirty processes such as the laser cladding. The cladding powder indeed coming from the powder cone is likely to interact with the optical elements of the cladding head. As a result the optical elements become locally opaque and absorb the laser beam, with consequent thermal deformation, coating damage and lens breakage. The protective glass, that divides the focusing and collimation lenses from the dirty work area, has the fundamental role to protect the entire optical chain and represents the element whose life has to be continuously monitored in order to avoid unexpected and unpleasant lens damages. This device is based on two different signals, the first one is the scattered light from the protective glass, and the second one is the temperature signal from the protective glass holder. The developed monitoring device is extremely compact and is able to recognize both small (*i.e.* cracks) and large defects (*i.e.* diffuse opacity) on the surface of the protective slide. In Figure 2 a complete graph of the monitoring system response is shown, here the different steps from the clean slide to a destroyed one are visible.

Conclusion

Both the developed monitoring device and the new cladding head (see Figure 3) have been tested in several cladding experimentations dealing with typical industrial cases, such as the cladding of worn dies, the turbine blades repairing and the anti-corrosion applications of extrusion threads for injection machines. The cover slide monitoring system and, in general, the laser cladding head prototype have worked for several days. The data, acquired during these days, confirm that the head prototype and the monitoring system are well designed and a valid equipment.