



***European Science Foundation***

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**Scientific Report of ESF/PESC Exploratory Workshop:**

**Advances and Opportunities in Freeform Ultra-Precision  
Micromanufacturing Technologies**

*Nottingham, United Kingdom, 22 - 23 November 2006*

**Convened by**



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### From left to right

**Back row** (standing): Eugen Trapet, Amir Fahmi, Oltmann Riemer, Per Gustafson, Mihai Nicolescu, Arnauld De Grave, Enrico Savio, Philippe Lutz, Jan Kotschenreuther, Wolfgang Knapp

**Front row** (sitting): Hans Nørgaard Hansen, Marioara Avram, Robert Ching, Leonardo De Chiffre, Dragos Axinte, Günter Wilkening, Jan Peirs, Joe Armstrong



## 1. Executive summary

The Exploratory Workshop was convened by Dr. Dragos Axinte (University of Nottingham) and Prof. Leonardo De Chiffre (Technical University of Denmark) and it took place at School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, United Kingdom.

It was organised as a two half-day event (22/23 Nov 2006) aimed to act as a focussed forum for technical discussions in the field of generation, inspection and integration of freeform ultra-precision micro-manufacturing technologies.

For effective preparation and dissemination of information the following website address has been used: <http://mcm.nottingham.ac.uk/news/ESF.htm>. This was supported by University of Nottingham.

The event was sponsored by the European Science Foundation (EW05-107) and logistically supported by with University of Nottingham. Through ESF sponsorship long-distance travel costs have been covered enabling all the participants to arrive on 22<sup>nd</sup> November before 2.00pm when the event officially was opened by the Conveners and a welcomed speech by Prof. Tom Hyde addressed.

The Workshop was attended by 20 experts in various areas related to micro-manufacturing technologies from 10 different countries. Thus a good impact of the sheared information within European environment has been ensured.

The first half-day session (22<sup>nd</sup> Nov) of the workshop was dedicated to technical presentations (15 min) that were divided on three main topics:

Session 1 – Phenomena and particularities of Bits-Out  $\mu$ Manuf technologies

Session 2 – Quality control strategies of Bits-Out  $\mu$ Manuf processes

Session 3 – Technology integration to construct Bits-Out  $\mu$ Manuf cells.

Each session comprised 4-5 presentations followed by 30 min break that stimulated interactions between the invitees.

Prior to the official opening of the Workshop a number of 7 posters had been accommodated within the conference room. This enabled further technical discussions among the participants during the breaks.

The second half-day session (23<sup>rd</sup> Nov) of the workshop started with the poster presentations (10 min each) followed by short discussions and demonstrations. The discussions were focused to attain the following main objectives of the workshop:

- Review/update the current Bits-Out  $\mu$ Manuf technologies and evaluate their performances /limitations. Thus, the research/engineering community defined sound ground from which further developments on  $\mu$ Manuf technologies could be made.
- Critical evaluation of the modelling methods of Bits-Out  $\mu$ Manuf technologies and modalities to overcome their deficiencies/limitations. This enabled the definitions of more efficient control of process parameters to achieve the required output measures of the manufactured micro-freeforms.
- Identify possible new Bits-Out  $\mu$ Manuf techniques. This was achieved through the formation of research consortia to look for European /industrial research funding to explore the new  $\mu$ Manuf techniques.
- Define the features and the methodology to construct “self contained”



miniature  $\mu$ Manuf cells. This enabled an integrated approach towards the manufacture and the part quality inspection at low energy consumption per number of micro-machined component.

- For educational/training purposes, relevant lists of academic/R&D institutions with expertise in Bits-Out  $\mu$ Manuf technologies was compiled. This will assist in establishing/update academic curricula, student exchanges and educational demonstrations and further facilitated through collaborative education actions among the workshop participants.
- Logistically, data on the expertise, ongoing/future projects, experimental /modelling capabilities and industrial collaborators/end users in the field of Bits-Out  $\mu$ Manuf was collected from the workshop participants. This will facilitate research collaborations and liaison with R&D/industrial organisation for promoting future relevant research projects.

## 2. Scientific content of the workshop

**Oltmann Riemer** (University of Bremen, Germany) presented on micro-Cutting of Freeforms, Microparts and Microstructures. He pointed out that nowadays several qualified technologies have been established for the manufacturing of precision parts and micro structured surfaces in the field of MEMS, e.g. lithography, etching, LIGA, laser beam, ion beam or electron beam machining. However, mechanical processes, e.g. micro milling and turning, diamond machining, engraving, forming and moulding, play also a significant role for the generation of microstructure and freeform surfaces and the manufacture of microparts. Major aspects of mechanical manufacturing methods for freeforms, microparts and microstructures were introduced and discussed. Potentials, advantages, challenges and applications of precision machining processes like turning, milling and drilling using miniaturized cutting tools as well as monocrystalline diamond tools were discussed taking into account machining parameters, tool design, and measuring techniques.

**Ian Pashby** (University of Nottingham, United Kingdom) presented advances on micro-erosion ( $\mu$ -EDM) of metallic alloys. He showed evidence that EDM fast hole drilling is one of the most important applications of sub millimetre Electro Discharge Machining. The process is used extensively to drill precision holes in aerospace parts; holes that provide cooling air that is essential for modern gas turbine engines to function. Given the number of holes required, hundreds of thousands in each engine, process optimisation in terms of drilling speed and electrode wear is very important. However, the process is complex with many significant variables and interaction of individual factors. A systematic, statistical approach has been adopted to the drilling of 0.6 mm holes in a Nickel based super alloy using brass electrodes and de ionised water dielectric. The critical factors and interactions have been identified and the information used to produce process models, these models have then been verified.

**Jan Peirs** (Katholieke Universiteit Leuven, Belgium) presented applications on Micro-EDM of semiconductors and ceramics. He showed interesting techniques for freeform micromachining of conductive ceramics and highly doped semiconductors. Besides the common material removal mechanisms (melting and evaporation), two additional mechanisms can occur with these materials: spalling and decomposition. Spalling occurs when material is removed by cracks generated by high-energy sparks. Spalling increases the machining speed, but the debris may disturb the process and residual cracks in the workpiece are a major concern. Material decomposition occurs with  $\text{Si}_3\text{N}_4$  due to the high



temperature of the plasma, resulting in a high surface roughness. A minimal surface roughness of  $0.77 \mu\text{m Ra}$  was obtained for a  $\text{Si}_3\text{N}_4$  - TiN composite, compared to  $0.35 \mu\text{m Ra}$  for  $\text{B}_4\text{C}$  -  $\text{TiB}_2$ ,  $0.4 \mu\text{m Ra}$  for  $\text{SiC}$ ,  $0.45 \mu\text{m Ra}$  and  $\text{ZrO}_2$  - TiN. Surface roughness, microcracks and residual stresses are a major concern for these brittle materials as they can drastically reduce strength and fatigue resistance.

**Jan Kotschenreuther** (University of Karlsruhe, Germany) presented results on efficient micromachining of hardened steels by a combination of laser ablation and EDM. - Ablating processes gain more and more importance in micro manufacturing. Technologies like EDM (electrical discharge machining) and laser ablation are both suitable for a non-contact material removal process and thus a material removal without any process forces – irrespective of mechanical material properties such as hardness or tensile strength. By laser ablation smallest structures can be realized with good surface qualities, while EDM facilitates higher ablation rates and aspect ratios. With the combination of both processes the specific advantages can be utilized while disadvantages can partially be eliminated. For this reason the Institute of Production Science examines integrated machining by EDM and laser ablation without reclamping in a single machine tool. The processing time of a micro gear wheel has been reduced by more than 50 % and the initial surface quality of an EDM-processed plane has been significantly improved.

**Günter Wilkening** (Physikalisch-Technische Bundesanstalt, Germany) commented on various aspects of micro-metrology - Production as well as research and development need adequate, quantitative metrology. In micro technology, the measurement tasks are manifold and besides the generally accepted CMM technology, a number of different measurement methods are realised in commercial instruments. In practice, adapted standards are the most efficient way to calibrate the respective instruments and thus verify the traceability of measurements. There are a number of well-established calibration standards in measurement technology for macroscopic objects, which can be used in micro metrology, or scaled down. Also, there are some standards known from the semiconductor technology which can be used for calibration purposes in micro metrology, like line scales, grids, step height structures and line width structures. However, there is a need for standards which are adapted to specific requirements of micro technology, like c.f. its 3-dimensionality, and which are suitable for mechanical, as well as optical probing. The talk discussed general measurement capabilities of instruments and methods in the context of measurement tasks and required uncertainties in micro metrology, gave an overview of existing standards which are used in micro metrology, and addressed the status concerning written standards in this field.

**Eugen Trapet** (Unimetrik, Spain) presented the new advances on Micro-CMMs of micro-parts - The rapid progress of complex 3D micro parts' manufacturing asks for corresponding 3D measuring technologies in order to verify parts, to develop and to control processes. Only since very recently commercial micro- and nano measuring machines are available which are expected to fully develop during the next 10 years into systems which are as flexible and universal as today's multi-sensor coordinate measuring machines in the world of macro parts manufacturing. In this presentation the basic concepts of micro and nano measuring machines, their probe systems, and their state of the art calibration methods were discussed. Furthermore the limitations of nowadays machines with respect to the measurement of more complex 3D micro structures were analyzed. Approaches for remedies were presented as they are to be developed



in a European-funded project (Nano CMM); central tasks are here the development of tactile and optical probes with about 0.2 micrometer effective probe tip size (structural resolution), of probe changers and of micro rotary stages for rotating the object without losing the object coordinate system, in order to measure the object from all sides and inside holes and grooves of a few micrometers diameter, in one object clamping. New verification standards and suited reference objects are under development.

**Enrico Savio** (Padua University, Italy) discussed various aspects of micro-freeform metrology - Quality control in manufacturing is essential to guarantee conformance to geometrical product specifications. The difficulties of micro-manufacturing technologies are even bigger for the measuring technologies, due to the limitations in terms of measuring range, accuracy and speed. The inspection of freeform geometry is a complex task itself, and at the microscale the challenge is even bigger; the presentation reviewed the available metrology tools for the inspection of freeform geometry at the microscale. First, the requirements of a typical freeform inspection task were identified. The most important measuring techniques were then discussed, with focus on freeform measuring tasks. Accuracy and traceability issues were also considered.

**Wolfgang Knapp** (Institute for Machine Tools and Manufacturing, Switzerland) discussed on micro-machine tool testing - Testing of micro coordinate measuring machines is looked at first, in order to get to know already applied methods, their benefits and problems. Then single axis tests (positioning, straightness, roll, pitch, yaw for linear axes, radial, axial and tilt movements for rotary axes) shall be looked at their applicability for micro-machines, respectively how these tests had to be changed to be used on micro-machine tools. Location errors between axes (squareness, parallelism, position of rotary axes) are the next group of tests to be checked for their applicability on micro-machines. Kinematics tests for checking numerical control, interpolation, backlash and as integral tests for calibration, e.g. diagonal displacement tests, circular tests, R-tests, are considered for micro-machine tools. Here the potential of "internal" kinematics tests, which just use the machine tool's scale read-out are discussed. Thermal tests shall help understanding and detecting sources of any drifts. How those tests can be applied on micro-machine tools shall be discussed. This shall also give the basis for defining criteria for the thermal environment. Dynamic tests, at least for vibrations introduced from the machine tool's environment have to be considered. Finally this shall help defining vibration criteria for the machine tool's environment. Setting up for machining by part alignment and tool location identification are further topics, which should be addressed, including testing the performance of any methods applied. Finally, manufacturing and measuring test pieces is an option for micro-machine tool testing, strongly dependant on the availability of appropriate measurement technology for micro-workpieces, which is another important issue for micro-machining.

**Dragos Axinte** (University of Nottingham, United Kingdom) presented some of the latest developments of micro-machine tools - Workshop size machine tools for ultra-high precision machining are being developed, while, sometime, their size and energy efficiency are in contrast with that of the micro-components being produced. Although, the desktop machine tools raise difficulties in construction and integration of electro-mechanical components, they might be a route towards space and energy intensive future micro-manufacturing systems. The use of recent developments in miniaturisation technology (e.g. multi-axis tables with nanometric resolution, ultra-high speed spindles, sensing systems) can offer technical solutions for construction of miniature dedicated machine



tools leading towards the achievement of ultra-high accuracy in micro-machining operations. Latest developments into building miniature machine tools using available/customary electro-mechanical, control and inspection systems are presented and their performances discussed. Then, future trends and challenges into miniaturisation of machine tools and their field of applications are commented.

**Per Gustafson** (Sandvik-Coromant, Sweden) commented on the demands on cemented carbide grades for micro-machining tools. - Cemented carbides have found extended usage in a variety of applications. The demand on a cemented carbide grade varies depending on the intended usage. In very fatigue and toughness demanding applications, grades with coarse tungsten carbide grain size in combination with low binder phase content have been found favourable. Turning of steel most often require grades with an intermediate WC grain size with additions of cubic carbides whereas milling and drilling applications favour more fine grained grades with less or no cubic carbide added. Developing of grades for a specific application such as micro-machining requires an understanding of how a demand is affected by the application and how the properties can be changed in order to fulfil the demands. The presentation discussed the demands on cemented carbides used in micro-machining application and present recent development within the industry in order to better fulfil these requirements.

**Philippe Lutz** (Laboratoire d'Automatique de Besançon, France) discussed various aspects related to micro-sensors for micromanipulation and micro-assembly. He presented new developments on micro robots to perform various tasks in the so-called *Microworld* (i.e. the world of sub-millimetric objects), in particular micromanipulation tasks of single objects (artificial or biological) for positioning, characterizing or sorting as well as for industrial micro-assembly. Closed-loop control of the micro robots requires the integration of very small sensors and the use of bulky and expensive instruments for signal processing and real-time operating. Connector technology and integration of the sensors and actuators are also hard problems. He presented a particular need to perform micromanipulation or micro assembly tasks in an automatic mode: the force feedback. The different way to make the force feedback was explained and proposed for other different applications. Comments were made on the performances using two gages stuck on a piezo electric cantilever. The resolution of the sensor is  $1\mu\text{m}$  and the cantilever can produce  $\pm 100\mu\text{m}$  deflexions and  $\pm 81\text{mN}$  forces. The performances of this system in a closed loop control to perform a pick and place task were given. The proposed system is developed as part of the EUPASS project (Evolvable Ultra-Precision Assembly Systems).

**Hans Nørgaard Hansen** (Technical University of Denmark, Denmark) commented on micro-production using Bits-out technologies. - Micro products can be characterised as having at least one critical dimension or functional feature in the sub-mm range. The production of such micro components requires the use of processes usually combined into complex process chains. The choice of processes depends largely on the material involved and on the complexity and characteristics of the components. For micro products in metals, polymers or ceramics down-scaling of macro-scale production technologies is a suitable way forward. This however poses challenges in terms of the so-called size effects and also the supporting technologies such as handling, assembly and metrology are largely affected by the down-scaling. The presentation focused on the challenges of process chain realisation when freeform surfaces have to be produced for example using replication processes.



**Svetan Ratchev** (University of Nottingham, United Kingdom) discussed on synergetic process integration for efficient micro and nano manufacture and in particular on initial road mapping results - Micro/nano-manufacturing technologies are becoming a source of major competitive advantage in sectors such as consumer electronics, automotive, healthcare and defence industries. The presentation discusses presents some of the early road mapping results part of the EU funded coordination action project  $\mu$ SAPIENT. The  $\mu$ SAPIENT project included 18 partners and its aim is to prepare the European industry for a move from designing MST-based products for specific materials and technologies (platform and technology push products) to adopting new disruptive processes/process chains to satisfy specific functional and technical requirements of new emerging multi-material products. In particular, this should lead to the creation of meso/micro-products that are less process intensive and are more focused on integrating functions and broadening product capabilities. In this context, a step change is required in the mentality of designers and manufacturers of MST and micro-engineering products. Such a change should be supported by a systematic analysis of research outputs of many EC, national and industrially funded projects in the field of MNT to facilitate process design and integration that is product-driven. Ultimately, this should lead to a better exploitation of the application potential of new generic MNT by European companies. The early road mapping activities have been focused on 4 distinctive areas: markets, products, process and equipment.

**Poster presentations** were given by:

**Robert Ching** (Queensgate Instruments, United Kingdom) commented on the design and characterisation of an ultra-precision X-Y table developed by Queensgate Instruments - The Queensgate NPS-XY-100A is a two axis closed loop positioning and scanning stage with an envelope of 100 x 100 x 23 mm with a 40 mm diameter aperture. Constructed wholly from Super Invar, it offers > 120 x 120  $\mu$ m positioning and scanning range. Position noise is typically 0.3 nm (rms) and linearity error (compensated with a 4th order polynomial in the electronics) is less than 0.01%. Hysteresis and parasitic angular motions are controlled to less than 0.005% and 10  $\mu$ rad, respectively, over the whole travel range. The first resonant frequency of the stage is > 350 Hz.

**Joe Armstrong** (Taylor Hobson, United Kingdom) presented some aspects of the company's experience on 3D characterisation of  $\mu$ -surfaces - The study of surface metrology is becoming commonplace in industrial and research environments. The need for accurate metrology measurement is also becoming more and more important as surface specifications become very tight. The change in high-resolution metrology requirements has lead to more and more technologies now available for studying surface metrology. All of the available technologies have its own set of typical applications but often selecting the correct metrology tool for the desired measurement can be quite difficult, depending on the material, environment, property and measurement required. Stylus profilometry, white light interferometry and confocal microscopy are common techniques used to measure surface metrology and the strengths and weaknesses of each of the techniques are discussed with examples.

**Arnauld De Grave** (Technical University of Denmark, Denmark) presented two case studies which require micro-manufacturing technologies, namely: medical bio-chips for point of care (requiring micro channels on credit card size chips); micro components for hearing-aid devices (requiring functional downscaled design from a typical "macro" design, with pivot links, translation links, spring).





**Amir Fahmi** (University of Nottingham, United Kingdom) presented an application of magnetorheological fluids for reconfigurable fixturing systems to assist micro-manufacturing processes to enable orientation and holding freeforms.

**Marioara Avram** (IMT Bucharest, Romania) presented the use of UV photolithography (positive and negative photoresists – FL); nanolithography; metal deposition, dry etching, thin electric layer deposition to generate micro-devices (microgears, micro-pumps, micro-channels) for bioengineering applications.

**Hans Nørgaard Hansen** (Technical University of Denmark, Denmark) presented various technical aspects stemming from the Danish micro-factory experience including micro-machining, micro-forming as well as challenges of their implementation on large scale productions.

**Mihai Nicolescu** (Royal Institute of Technology, Sweden) presented intelligent fixturing solutions for micro-machining capable to actively damp vibrations. These innovative fixtures have extensive use in manufacturing of high precision optical micro-devices.

### **3. Outcomes and results**

The participants to the workshop identified gaps in understanding the particularities of processing techniques of micro-freeforms and their utilisation in medical, aerospace and optical industries. Minutes of the discussions have been taken and later circulated to the participants for their input and comments.

A collection of all the presentations will be submitted to all the participants and ESF – Exploratory Workshop responsible.

The participants that collaborated to the EUROCORES THEME proposal (06-ETHEME-024) that has not been supported by ESF decided to further support for resubmission to the follow-up calls. The proposal will be improved based on the feedback of the assessors and the information shared during the workshop.

A new theme for a FP7 proposal has been identified and 8 academic/research institutions have expressed their interest into the topic. Steering group has been formed (Nicolescu - KTH, Hansen - DTU, Axinte – Univ. of Nott., Riemer – Univ. of Bremen) to further pursue the initiative. Notes on the initial idea of the project will be circulated after the new FP7 call will be online.

A follow-up meeting will be organised in the beginning of 2007 to pursue both micro-manufacturing initiatives. Venue to be agreed.

The participants expressed their satisfaction on the organisation of the event. Informal discussions continued after the workshop followed by a tour of the facilities existent within the Advanced Manufacturing Research Group, School of M3, University of Nottingham.



## 4. Final programme

**Wednesday 22 November 2006**

<b>Morning</b>	<b>Arrival</b>
13.30 - 14.30	Registration and Buffet Lunch
14.30 - 14.45	Welcome address: Convenors and representatives of University of Nottingham
<b>Presentation Sessions</b>	
<b>Session 1 – Phenomena and particularities of Bits-Out <math>\mu</math>Manuf technologies</b> <b>Moderator: <i>Dragos Axinte</i></b>	
15.00 - 15.15	P1 Micro-cutting of freeforms, microparts and microstructures, <b><i>Oltmann Riemer</i></b>
15.15 - 15.30	P2 Micro-erosion ( $\mu$ -EDM of metallic alloys), <b><i>Ian Pashby</i></b>
15.30 - 15.45	P3 Micro-EDM of semiconductors and ceramics, <b><i>Jan Peirs</i></b>
15.45 - 16.00	P4 Efficient micromachining of hardened steels by a combination of laser ablation and EDM, <b><i>Jan Kotschenreuther</i></b>
16.00 - 16.30	Coffee break
<b>Session 2 – Quality control strategies of Bits-Out <math>\mu</math>Manuf processes</b> <b>Moderator: <i>Leonardo De Chiffre</i></b>	
16.30 – 16.45	M1 Aspects of micro-metrology, <b><i>Günter Wilkening</i></b>
16.45 – 17.00	M2 Micro-CMMs, <b><i>Eugen Trapet</i></b>
17.00 – 17.15	M3 Micro-freeform metrology, <b><i>Enrico Savio</i></b>
17.15 – 17.30	M4 Micro-machine tool testing, <b><i>Wolfgang Knapp</i></b>
17.30 – 18.00	Coffee break
<b>Session 3 – Technology integration to construct Bits-Out <math>\mu</math>Manuf cells</b> <b>Moderator: <i>Mihai Nicolescu</i></b>	
18.00 – 18.15	T1 Aspects of the developments of micro-machine tools, <b><i>Dragos Axinte</i></b>
18.15 – 18.30	T2 Demands on cemented carbide grades for micro machining tools, <b><i>Per Gustafson</i></b>
18.30 – 18.45	T3 Micro-sensors for micromanipulation and micro-assembly, <b><i>Philippe Lutz</i></b>
18.45 – 19.00	T4 Micro production using bits-out technologies, <b><i>Hans Nørgaard Hansen</i></b>
19.00 – 19.15	T5 Synergetic process integration for efficient micro and nano-manufacture: Initial road mapping results, <b><i>Svetan Ratchev</i></b>
19.15 – 19.30	Shuttle Bus from University Park Campus to Innkeeper's Lodge
20.00 – 22.30	Dinner



## Thursday 23 November 2006

08.30 – 09.00	<i>Shuttle Bus from Innkeeper's Lodge to University Park Campus</i>
<b>Discussion and Poster Session (PS) Sessions</b>	
<b>Session 4 – Poster presentations and discussions</b>	
09.00 - 09.45	Posters <ul style="list-style-type: none"><li>• <math>\mu</math>-positioning systems, <b>Robert Ching</b></li><li>• KTH <math>\mu</math>-fabrication initiative, <b>Mihai Nicolescu</b></li><li>• Danish <math>\mu</math>-factory, <b>Hans Nørgaard Hansen</b></li><li>• <math>\mu</math>-manufacturing, <b>Amir Fahmi</b></li><li>• <math>\mu</math>-fluidic system for biomedical applications, <b>Marioara Avram</b></li><li>• <math>\mu</math>-product functionality requirements, <b>Arnauld De Grave</b></li><li>• 3D characterisation of <math>\mu</math>-surfaces, <b>Joe Armstrong</b></li></ul>
<b>Session 5 – Roundtable discussions</b> <b>Moderators: Dragos Axinte and Leonardo De Chiffre</b>	
09.45 - 12.15	<ul style="list-style-type: none"><li>• Commentaries/remarks on the previous day presentations</li><li>• Technical debates on future developments of <math>\mu</math>Manuf technologies</li><li>• Brainstorming on future integrated <math>\mu</math>Manuf systems</li><li>• Draft roadmaps - gaps, research strategies, drivers, enablers</li><li>• Identifying vehicles for further research and collaborations</li><li>• Educational and logistic aspects of <math>\mu</math>Manuf technologies</li></ul>
12.15 - 12.30	Closing remarks
12.30 - 13.30	Buffet lunch
13.30	Departure

## 5. Statistical information on participants

**Age structure:** 30-40 years old (5), 40-50 years old (9), 50-60 years old (6).

**Countries of origin:** Belgium (1), Denmark (3), France (1), Germany (4), Italy (1), Romania (1), Spain (1), Sweden (2), Switzerland (1), United Kingdom (6).

**19 Men and 1 Female** participants.

## 6. Final list of the participants

1. Leonardo De Chiffre, Technical University of Denmark, Department of Manufacturing Engineering and Management, Building 424, 2800 Kgs. Lyngby, Denmark, [ldc@ipl.dtu.dk](mailto:ldc@ipl.dtu.dk)

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19. Arnauld De Grave, Technical University of Denmark, Department Manufacturing Engineering and Management, Building 424, 2800 Kgs. Lyngby, Denmark, [adg@ipl.dtu.dk](mailto:adg@ipl.dtu.dk)

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