Analysis and Characterization of Machined Surfaces with Aesthetic Functionality

The generation of fine machined surfaces with high gloss is an important topic in mould manufacturing. The surface gloss can be characterized by means of scattered light sensors and a representative parameter such as $A_q$. In this paper, in-line measurements of scattered light distribution are compared with roughness parameters calculated using a confocal microscope, in order to assess surface aesthetic quality. Several surfaces have been machined by means of high precision milling, producing different surface topographies. Surface characterization has been performed on a machine using a scattered light sensor, and using a confocal microscope in laboratory conditions. The calculated $A_q$ parameter is compared with the amplitude roughness parameters $S_a$ and $S_q$, and with hybrid parameters $S_dq$ and $R_dq$ representing the average slope of the surface features. Scanning electron microscope (SEM) images are used as visual benchmarks to identify the parameters' correlation with the visual appearance. A different linear trend of the relationship between $A_q$, $R_dq$, and $S_dq$ is observed. The description of the surface quality through $S_a$ or $S_q$ instead is found to be insufficient. This is explained by means of SEM pictures showing a dramatic influence of the smeared material over the machined surface.

Assessment of the inflatable core assisted paper bottle moulding process

Eco-friendly products have gained importance in recent years. The paper bottle is a sustainable packaging solution for carbonated beverages. The moulding process is a two-stage process. At first, pulp is poured in the forming mould and fibers are formed in the desired shape. Wet bottle is then transferred to the drying mould to remove bound water. The drying process makes use of an inflatable core, which not only prevents the shrinkage of fibers but also helps in attaining good fiber compaction. Preliminary investigations reported uneven fiber compaction in changing curvatures and sharp corners. A cause of uneven thickness distribution in the geometry is uneven compaction pressure during core expansion. A FEM approach is developed to predict the occurrence of non-conformities in the bottle. Hyperelastic core material is modelled using Mooney-Rivlin material model from the elastic strain density function. The model can be used to optimize the core shape, thus developing a robust tooling solution.
A study on the feasibility of in-process compensation of cutting force induced errors using axes motors absorbed current

Portable machine tools are developed to address specific applications needs, such as machining of large components. However, they lack in performance such as stiffness. For such a low-stiffness portable machine tool, in this work, it is analysed the possibility and feasibility of employing the motors absorbed current measurements during actual machining operations as a means to monitor the cutting process and eventually compensate the tool deformations due to the cutting forces. In-process tool-path compensation achieved through a sensorized machine is of extreme interest from the costs point of view, especially for portable or dedicated task machine tool. In this paper, measurements of cutting forces, feed axes and spindle motors absorbed currents were carried out simultaneously for different cutting conditions. It is found that good correlations can be established between specific feature of the cutting force and axis motors absorbed current, the result demonstrates that the absorbed current measurements are reliable indirect measurements of the cutting forces and can therefore be employed in an in-process tool-path compensation.

Effect of cutting edge micro geometry on surface generation in ball end milling

Surface generation in machining processes is affected by a complex interaction between cutting edge and workpiece material, leading to surface artefacts, so that the surface topography deviates considerably from the kinematic one. This paper shows how to model such interaction, taking into account cutting edge topology, material deformation and cutting edge trajectory errors to achieve a reliable prediction of surface topography generation in ball end milling. The model is experimentally validated in upward raster ball end milling of copper and tool steel.
Micro product and process fingerprints for zero-defect net-shape micromanufacturing
Highly miniaturized systems find applications in key technological fields such as health-care, mobility, communications and optics. Required innovations for precision manufacturing of micro components can be achieved through post-process and in-process measurement of process input and output parameters. Hence, it is of critical importance to reduce the measurement and optimization effort, since process and product quality control can take a significant part of the production time in micro manufacturing. To solve this challenge, research is undertaken in order to define, investigate, implement and validate the “Product/Process Micro Manufacturing Fingerprint” concept. In particular, in the Horizon2020 Innovative Training Network “Process Fingerprint for Zero-defect Net-shape MICROMANufacturing”, 9 beneficiaries and 14 industrial partners are collaborating to establish this concept for several manufacturing technologies, such as micro injection and micro ultrasonic moulding, micro mechanical and micro plasma polishing, micro electrical discharge machining, micro electrochemical machining, micro grinding, micro laser machining, micro extrusion, micro metrology, micro sintering. The project has reached its goals of developing novel methods in micro scale manufacturing process monitoring and control, as well as micro and sub-micro product quality assurance. The overall result has been the establishment of effective micro product and process fingerprints for the considered manufacturing technologies.

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Organisations: Department of Mechanical Engineering, Manufacturing Engineering, University of Bradford, University of Bremen, Chemnitz University of Technology, KU Leuven, University of Nottingham, Politecnico di Milano, University of Strathclyde, Freiberg University of Mining and Technology
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Offline tool trajectory compensation for cutting forces induced errors in a portable machine tool
Portable machine tools are designed to reduce costs and resources necessary to perform dedicated tasks, such as milling of large components like wind turbine hubs. Such machines however lack in performance (e.g. stiffness, accuracy, thermal stability) with respect to conventional machine tools and may require compensation strategies to guarantee adequate accuracy. An offline compensation methodology, involving tool trajectory modification, based on the calculation of tool center point displacements from prediction of cutting forces and static stiffness characterization was implemented on a portable machine tool. The offline compensation was validated through a posteriori comparison with the nominal cutting conditions.

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Publication information
Process characterization for molding of paper bottles using computed tomography and structure tensor analysis

Packaging products find their significance in almost all classes of consumer goods and products. The use of plastic and metal based packaging for beverages is highly dominant. However, there is a constant urge for development of eco-friendly packaging alternatives. The article focuses on characterizing an inflatable core assisted paper bottle molding process with respect to the obtained fiber distribution in the bottle. Distribution of paper fibers affect product characteristics such as thickness and mechanical strength of the bottle. Assessment of fiber orientation using structure tensor analysis is therefore performed. The results confirmed non-uniform fiber compaction in the paper bottle. This gives rise to non-conformities such as non-uniform thickness distribution. The approach discussed in the work can be utilized as a Non Destructive Testing technique to evaluate the quality of paper bottles.

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Organisations: Manufacturing Engineering, Department of Mechanical Engineering, Department of Physics, Neutrons and X-rays for Materials Physics, Image Analysis & Computer Graphics, Statistics and Data Analysis, Department of Applied Mathematics and Computer Science
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Thermal characterization of a micro polishing machine and effect on path strategy compensation

Micro polishing is an important process when fine surface quality and low form error are required in the micro scale domain. This process has several differences from conventional polishing and some of the factors can not be neglected any longer. In this work, a study on the thermal behaviour of a micro hexapod-based machine is conducted. The main causes of thermal deformations are addressed and analysed. The contributions are then evaluated and compensation path strategies are discussed. The main criticalities when dealing with micro polishing are due to the small tools used. Micro tools require higher speeds than conventional polishing. High spindle speeds generate heat and therefore thermal deformations. This adds up to the movement of the Hexapod while performing polishing. The observed total deformation in the polishing tool axial direction reached 8.2 μm. Such a large deformation can introduce a potential error in the final material removal up to 50% if not adequately compensated.

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Organisations: Manufacturing Engineering, Department of Mechanical Engineering
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Additive Manufacturing of Mould Inserts with Mirror-like Surfaces

Selective laser melting (SLM) is often applied in the production of steel moulds with high wear resistance and conformal cooling channels for advanced thermal management. The surface finishing of such moulds is crucial, especially if it is intended for the moulding of plastic parts with aesthetic functionality. The surface quality of such metal 3D printed moulds is typically refined by means of subsequent material removal processes, but this is often hindered by residual porosity and inhomogeneity in the metal structure of the 3D-printed part.

In this paper an indirect tooling process chain for production of mould inserts is proposed. The process chain aims at exploiting the good replication capability of electroformed nickel, to copy mirror-like substrates. The bulky part of the insert is produced by means of SLM that shows a considerably higher material deposition rate. The thermal input is controlled throughout the process chain to prevent deleterious grains growth in the nickel layer.

The roughness of the nickel surface is measured after the selective etching of the substrate and compared with the substrate roughness before the nickel deposition, showing good replication of the master surface. The proposed process chain overcomes the problems related to the deposition of thick electroformed coatings by coupling electroforming with higher output additive processes such as SLM - that furthermore allows the introduction of cooling channels in close contact with the mould surface.

A mechanistic model for the prediction of cutting forces in the face-milling of ductile spheroidal cast iron components for wind industry application

Among renewable energy sources, wind energy has received considerable impulse in the last decade. Not only the number of manufactured wind turbines is raising, but also the overall size of the components is increasing, for improved energy harvesting. The increase of hub dimensions implies the need for larger, tailor built, milling machines, with impact on production costs and the possibility of local production. Within this scope, accurate prediction of process loads during the machining operations plays a central role with respect to the exploration of design solutions and processing strategies while maintaining the necessary product quality. For this purpose a mechanistic model, based on the unified cutting
mechanics theory, was developed for the prediction of cutting forces in face milling using inserted cutters, for the machining of ductile spheroidal cast iron. Ductile cast iron alloys are particularly prone to generate segmented chips. The applicability range of the fundamental model, the shear plane model underlying the unified mechanics of cutting, was studied for this phenomenon. A method was proposed to analyse chip segmentation and extract relevant data for the model implementation. Through experimental validation, it was proved that mechanistic models are a reliable option for modelling machining operation even under chip segmentation conditions.

Applicability of Acoustic Emission monitoring to micro polishing

Application of process monitoring solutions to micro polishing is affected by the low intensity of the measured signals, which influences the capability to extract useful information. This work explores the applicability of acoustic emission monitoring for detection of process completion through End Point Detection (EPD) in micro polishing. Several polishing tests have been conducted by gradually reducing the contact area and the acoustic emission signal generated by the process is acquired and analysed. The work shows that the monitoring solutions applied in conventional polishing can potentially be applied to the micro process.

Comparison of selected processes for surface microstructuring of complex mould for an implanted device

Polymer products with functional surfaces are applied in many fields such as medical devices and biotechnology. However, most technologies for the fabrication of microstructured functional surfaces are still limited to flat geometries or geometries with constant curvature. This paper describes and compares three approaches for fabricating micro- or nanostructured surfaces; those process chains are suitable for patterning of the surface of 3D shape cavity for injection
moulding. The desired surface features have been approved by cell proliferation test. The first approach is to use prefabricated plate with microstructured surface as an insert inside the cavity. The second approach is to directly pattern the surface by a femtosecond laser combined with mask projection technique. The third approach is to produce the cavity part using an anodizing process followed by metal deposition, and in this way, sub-microfeatures were obtained all over the cavity surface. The aim of this paper is to find solutions to implementing the desired features on the entire surfaces of a 3D-shaped ring; this research will also benefit the production of other complex parts with functional micro- or nanostructured surface.

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Methodologies for characterization of smearing micro geometry on ball end milled tool steel surfaces
Manufacturing surfaces with nanoscale roughness by machining involves several material removal steps among which a final shallow cut to reduce the scallops height produced by the cutting tool geometry. When the cutting tool engages the workpiece with small depth of cuts, the thickness of the chip becomes comparable to the cutting edge radius. In this configuration, the material is not completely removed but it is deformed and smeared onto the surface, increasing the surface roughness. In this work two different methodologies are proposed in order to quantify the volume of the chip that is subjected to smearing phenomena. Measurements of volumes at such scale length are not straightforward, therefore a combination of confocal and electron microscopy techniques are used in a synergistic way to increase the robustness of the methodologies. The results will help in further understanding and modelling the occurring of the smearing phenomena in milling for finishing operations.

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Micro Machining Technologies for Micro Injection Mold Making
Tooling for Production of the Green Fiber Bottle

Ever since the invention of plastics, packaging has become extremely cheap and efficient. In recent times, the demand for more ecological packaging is increasing leading back to the roots of using naturally available resources, which are biodegradable. The manufacturing process of the Green Fiber Bottle (GFB) is based on moulding of wood fibers. The process is still at the research stage and not commercialized. Tooling is the most critical element in moulding and should be adapted to quick water removal techniques, such as Impulse Drying Technology. In this work, functional requirements for the development of a robust tooling solution are identified. Tooling alternatives are investigated and compared with the capacity to enable water removal. Characterization and assessment of porous tool materials using computed tomography are also outlined and discussed.

Application of silicone based elastomers for manufacturing of Green Fiber Bottle

Due to ever-increasing demand of sustainable products, eco-friendly packaging solutions are finding their importance in the paper packaging industry [1]. Green Fiber Bottle (GFB) is an alternative to plastic, glass and metal based packaging for beverages. The manufacturing of paper bottle is a two-stage process, where the wood fibers are first thermoformed in the desired shape followed by drying of the formed geometry [2]. To ensure the robustness of the bottle and to avoid shrinkage of cellulose fibers, the wet-formed bottle is pressurized using a silicone core. The core is inserted inside the drying tool and inflated. This keeps the wet bottle under pressure thereby enhancing formation of good hydrogen bonds, and hence providing good strength. The feasibility of the tool design concept is supported with Finite Element Model. The hyperelastic
behaviour of silicone is defined by the deformation energy function (W). To simulate the inflation action of the core, Yeoh's model is used for modelling of W. The strength of the GFB is correlated with the pressure the bottle can hold and the cut-off burst pressure from experiments is also reported in this work.

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Application of silicone based elastomers for manufacturing of Green Fiber Bottle
Due to ever-increasing demand of sustainable products, eco-friendly packaging solutions are finding their importance in the paper packaging industry. Green Fiber Bottle (GFB) is an alternative to plastic, glass and metal based packaging for beverages. The tool concept for manufacturing of paper bottle uses a silicone based elastomer as the core. The expansion of core in the tool resists shrinkage of paper during drying as well as helps in obtaining good fiber compaction. The feasibility of the tool concept in the production of GFB is discussed in this work.

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Characterization of smearing patterns in ball nose end milling process
Very shallow depth of cut are used in ball end milling finishing operation in order to minimize the chip thickness, therefore reducing the surface roughness. When the chip dimension reaches a certain thickness threshold (the minimum uncut chip thickness), the cutting dynamic switches from effective material removal to ploughing and smearing. Smearing effects can significantly enhance the surface roughness. Another important factor is the choice of the appropriate tool path, which strongly affect the tool engagement condition and surface roughness. In this work, smearing pattern produced on mould steel by cBN ball end mill, are characterized by means of SEM analysis. The results show that the location of the smearing pattern is strictly connected with the relative direction of cutting speed and feed and step over direction. Furthermore, a comparison with the theoretical chip thickness distribution confirms that the smearing of the material occurs in the area in which the chip thickness approaches to zero.

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Characterizing Green Fiber Bottle Prototypes Using Computed Tomography

Due to ever increasing demand of sustainability and biodegradability, there arises a need to develop environmentally friendly packaging products. Green fiber bottle is a packaging product for carbonated beverages, made out of cellulose fibers. The production process accounts for moulding paper pulp in the desired shape and structure. However, there are certain limitations associated to the product characterization using tactile measuring methods. In this work, a new approach has been applied for defect analysis and quality control of non-homogenous prototype paper products using computed tomography.

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Effect of TWD estimation error on the depth of machined cavities in micro-EDM milling

In micro-EDM milling, real time electrode wear compensation based on tool wear per discharge (TWD) estimation permits the direct control of the position of the tool electrode frontal surface. However, TWD estimation errors will cause errors on the tool electrode axial depth. A simulation tool is developed to determine the effects of errors in the initial estimation of TWD and its propagation effect with respect to the error on the depth of the cavity generated. Simulations were applied to micro-EDM milling of a slot of 5000 μm length and 50 μm depth and validated through slot milling experiments performed on a micro-EDM machine. Simulations and experimental results were found to be in good agreement, showing the effect of error amplification through the cavity depth.

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Contributors: Puthumana, G., Bissacco, G., Hansen, H. N.
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Moulded Pulp Manufacturing: Overview and Prospects for the Process Technology

Eco-friendly packaging such as moulded pulp products have gained commercial importance in the recent years. However, it remains a greatly under-researched area, and there is an arising need to consolidate the best practices from research and industry in order to increase its implementation. The goal of this paper is to give an overview of the main aspects involved in the manufacture of moulded pulp products. This includes a classification of moulded pulp products, historical and current applications, production processes, materials, mechanical properties and environmental sustainability. Moreover, based on the latest research in the field, an innovative drying technique that utilizes concepts derived from impulse drying is presented, and the implementation of this process technology is discussed.

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Acoustic emission-based in-process monitoring of surface generation in robot-assisted polishing

The applicability of acoustic emission (AE) measurements for in-process monitoring of surface generation in the robot-assisted polishing (RAP) was investigated. Surface roughness measurements require interruption of the process, proper surface cleaning and measurements that sometimes necessitate removal of the part from the machine tool. In this study, stabilisation of surface roughness during polishing rotational symmetric surfaces by the RAP process was monitored by AE measurements. An AE sensor was placed on a polishing arm in direct contact with a bonded abrasive polishing tool, and a cylindrical workpiece in Vanadis 4E steel was polished in 40 polishing passes from an initial turned surface.
roughness $Ra = 3.1 \mu m$ down to $Ra = 0.07 \mu m$. The polishing task was performed in five intervals and after 4, 8, 20, 30 and 40 passes, the resulting surface roughness was measured. The results show a decreasing trend in measured AE signal power and RMS, which is well qualitatively correlated with the development of surface roughness during polishing. The trend allows the identification of an asymptote representing the process completion (stabilisation of surface roughness), reliable for correct in-process determination of the process endpoint. This makes it possible to reliably determine the right time for changing the polishing media to finer abrasive when applying a given set of parameters is no longer effective to create a smoother surface, thus improving the efficiency of the process. The findings enabling automatic detection of optimal process endpoint allow intelligent process control, creating fundamental elements in development of robust fully automated RAP process for its widespread industrial application.

**A simulation of the effect of TWD (tool wear per discharge) estimation error on the depth of machined surfaces in micro-EDM milling**

**Comparison of cutting edge characterization techniques applied to industrial tools with sub micrometer edge radius**
Within micro and precision machining, cutting tool performance with respect to the ability to generate fine surfaces is largely determined by the size of the edge radius, which dramatically affects the minimum uncut chip thickness. In the recent years emphasis has been placed on cutting edge radius characterization. While the measurement techniques from literature can be well suited for ordinary tools with edge radii in the order of tens of microns, tools for fine finishing operations, exhibit edge radii in the sub-micrometer range, which limit the robust applicability of such techniques. This paper presents an investigation on the characterization of ball nose end mill cutting edges with sub micrometer edge...
radius. For this purpose CBN and WC tools cutting edges were characterized by means of a confocal microscope (Olympus Lext OLS4100). The measurements were validated through reference AFM measurements and the data fitted with known cutting edge determination algorithms. The influence of the roughness of rake and clearance face on the robustness of the edge radius calculation is discussed and the capabilities and limitations of the methods are highlighted.

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**Computed Tomography characterization of the Green Fiber Bottle**
The work carried out in this research aims at identifying suitable ways for thorough characterization of the quality of paper bottles. Industrial X-ray Computed Tomography (XCT) is particularly advantageous in determining the quality of paper bottles and thus correlating it with the production process. The Green Fiber Bottle (GFB) is a freeform geometry consisting of cellulose fibers. Accurate dimensional measurements such as wall thickness of the GFB is not possible using Coordinate Measuring Machines (CMMs). XCT on one hand provides an effective means of measuring wall thickness and on the other hand it also helps in identifying voids in the order of 110 µm at any location in the bottle geometry.

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**Moulding process characterization of paper bottles using computed tomography**
The paper presents an approach of evaluating the moulding process for production of paper bottles using Computed Tomography (CT). Moulded Pulp Products (MPP) are made of a formed, dewatered and dried mixture of pulp fibers and water. Modern industrial pulp moulding is dated back to the year 1903 when a patent for MPP production was acquired by Martin L. Keyes. With an increasing demand for environmental friendly products, researchers are now focusing on investigating advanced manufacturing process for production of MPP.

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The effect of TWD estimation error on the geometry of machined surfaces in micro-EDM milling

In micro EDM (electrical discharge machining) milling, tool electrode wear must be effectively compensated in order to achieve high accuracy of machined features [1]. Tool wear compensation in micro-EDM milling can be based on off-line techniques with limited accuracy such as estimation of the volumetric wear ratio and continuous compensation proportional to the in-plane displacements (anticipated wear compensation) or real time wear sensing [2]. Tool wear per discharge (TWD) is a parameter based on which a novel approach has been developed for tool wear compensation based on discharge counting and statistical characterization of the discharge population [3]. The TWD based approach permits the direct control of the position of the tool electrode front surface. However, TWD estimation errors will generate a self-amplifying error on the tool electrode axial depth during micro-EDM milling. Therefore, accuracy of the tool wear compensation method as well as the geometry of the machined feature depends on the variability of TWD during machining operation. This paper analyses the effect of errors on the estimation of TWD on geometry of the machined features, in the case of a typical slot machining process. The error propagation effect is demonstrated through a software simulation tool developed by the authors for determination of the correct TWD for subsequent use in compensation of electrode wear in EDM milling. The implemented model uses an initial arbitrary estimation of TWD and a single experiment with determination of number of discharges and removed electrode volume. The simulation tool developed is used to calculate the effects of errors in the initial estimation of TWD on the propagation effect of error on the depth of the cavity generated. Simulations were applied to EDM milling of a slot of 5000 μm length and 50 μm depth, with a segment length of 100 μm and layer thickness of 1 μm. Simulations have been performed for TWD estimation errors ranging from -15% to +15%, see Figure 1: a. In order to validate the results obtained using simulations, slot milling experiments were performed on a SARIX SX-200 micro-EDM machine. Tungsten carbide rod of Ø300 μm and Stavax steel blocks were used as the tool material and workpiece material respectively. The programming for machining along the segments and along each layer was done using G codes. The population of discharge current signals were characterized for selection of the trigger level to count all the discharges contributing to the tool wear. Experiments were replicated five times to ensure the repeatability of the results. From the simulations, it is observed that the depth error due to TWD estimation error is magnified and transmitted in different progressions along the tool path. The simulation results show that a variation in TWD estimation error from +1% to +5%, the maximum error in the geometry of micro-EDM milled profile varied from +6.14% to +40.52%. It is observed that results of depth predicted using the simulation and the average depth obtained using experiments match thoroughly within an error of 5%, see Figure 1: b.

Application of Functional Nano-Patterning to Polymer Medical Micro Implants

Improvement of cells adhesion to medical implants can be achieved through specific surface nano-patterns. The application of nano-patterns to planar surfaces can be obtained in a number of ways. However, the application of functional nano-patterns to complex 3D surfaces is a challenging task. In this paper the application of a nano-pattern deriving from aluminium anodizing to 3D micro mould inserts for replication of polymer medical micro implants is described. A process chain earlier developed at DTU was applied, where the main steps include the fabrication of an aluminium master, anodizing, etching of aluminium oxide, nickel and copper electroplating and selective etching of the aluminium master. The resulting nanostructure consists of tightly packed hemispherical features with average diameter of approximately 400 nm. Characterization of the obtained nanostructure on the micro mould inserts was carried out by means of atomic force microscopy and scanning electron microscopy. Results show that the specific nano-pattern was successfully generated on the 3D mould inserts exploiting the proposed process chain.
Characterization methods of nano-patterned surfaces generated by induction heating assisted injection molding

An induction heating-assisted injection molding (IHAIM) process developed by the authors is used to replicate surfaces containing random nano-patterns. The injection molding setup is developed so that an induction heating system rapidly heats the cavity wall at rates of up to 10°C/s. In order to enable the optimization of the IHAIM process for nano-pattern replication, it is necessary to develop robust methods for quantitative characterization of the replicated nano-patterns. For this purpose, three different approaches for quantitative characterization of random nano-patterns are applied and compared. Results show that the use of IHAIM is an efficient way to improve replication quality. All three measurement methods are capable of detecting the trend of the replication quality of the surface changing the process condition.

Comparison of 3 methods on fabricating micro- /nano- structured surface on 3D mold cavity

The methods to manufacture micro- or nano- structures on surfaces have been an area of intense investigation. Demands are shown for technologies for surface structuring on real 3D parts in many fields. However, most technologies for the fabrication of micro-structured functional surfaces are still limited to flat or simple shaped geometries. In this paper, 3 approaches for fabricating micro and nano- structured surfaces on a mold cavity for injection moulding are investigated and compared. The first approach is to use pre-fabricated plate with micro-structured surface as an insert for the mold, in this way micro holes (Ø4 μm) was obtained. The second approach is to produce the cavity part using anodizing process chain, and in this way sub-micro structures can be obtained all over the cavity surface. The third approach is to machine the surface inside the cavity directly by femtosecond laser combined with mask projection technique.
Comparison of optical methods for surface roughness characterization

We report a study of the correlation between three optical methods for characterizing surface roughness: a laboratory scatterometer measuring the bi-directional reflection distribution function (BRDF instrument), a simple commercial scatterometer (rBRDF instrument), and a confocal optical profiler. For each instrument, the effective range of spatial surface wavelengths is determined, and the common bandwidth used when comparing the evaluated roughness parameters. The compared roughness parameters are: the root-mean-square (RMS) profile deviation (Rq), the RMS profile slope (Rdq), and the variance of the scattering angle distribution (Aq). The twenty-two investigated samples were manufactured with several methods in order to obtain a suitable diversity of roughness patterns. Our study shows a one-to-one correlation of both the Rq and the Rdq roughness values when obtained with the BRDF and the confocal instruments, if the common bandwidth is applied. Likewise, a correlation is observed when determining the Aq value with the BRDF and the rBRDF instruments. Furthermore, we show that it is possible to determine the Rq value from the Aq value, by applying a simple transfer function derived from the instrument comparisons. The presented method is validated for surfaces with predominantly 1D roughness, i.e. consisting of parallel grooves of various periods, and a reflectance similar to stainless steel. The Rq values are predicted with an accuracy of 38% at the 95% confidence interval.

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Comparison of two setups for induction heating in injection molding

To eliminate defects and improve the quality of molded parts, increasing the mold temperature is one of the applicable solutions. A high mold temperature can increase the path flow of the polymer inside the cavity allowing reduction of the number of injection points, reduction of part thickness, and moulding of smaller and more complex geometries. The last two aspects are very important in micro injection molding. In this paper, a new embedded induction heating system is proposed and validated and two different coil setups were tested and compared. An experimental investigation was performed based on a test geometry integrating different aspect ratios of small structures. Acrylonitrile butadiene styrene (ABS) was used as material, and different mold temperatures were tested. The replicated test objects were measured by means of an optical coordinate measuring machine (CMM). On the basis of the experimental investigation, the efficacy of the two induction embedded coils, with respect to improvement of replication quality, has been verified.

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Development of a multisensory arm for process monitoring in Robot Assisted Polishing

A multisensory polishing arm with integrated three component force sensor, a miniature acoustic emission (AE) sensor and an accelerometer was developed for process monitoring in Robot Assisted Polishing (RAP) process. The arm design was optimized for integration of a force and an AE sensor. The force sensor, consisted of semiconductor and metallic strain gauges, was calibrated by means of static application of defined loads. The sensor performance in a dynamic application was subsequently verified by comparison with a reference calibrated dynamometer on a dedicated test rig. To compensate for measurement bias caused by the inertial component due to the mass of the oscillating arm, acceleration is measured, inertia component calculated and subtracted from the measurements. The results demonstrate the suitability of the custom designed multisensory polishing arm for process monitoring in all RAP process configurations.

Development of a multisensory arm for process monitoring in Robot Assisted Polishing

Robot Assisted Polishing (RAP) process is capable of achieving surface roughness down to $Sa\ 10\ nm$ on industrial components. In RAP, a robot arm carries a polishing module with controlled contact force utilizing oscillating or rotating tools. In this work a multisensory polishing arm with integrated Acoustic Emission (AE), accelerometer and force sensors was developed and the reliability of force measurements for process monitoring in RAP was verified.
Development of an on the machine process monitoring and control strategy in Robot Assisted Polishing

Robot Assisted Polishing (RAP) can be used to polish rotational symmetric and free form components achieving surface roughness down to $Sa \ 10 \text{ nm}$. With the aim to enable unmanned robust and cost efficient application of RAP, this paper presents the development of a monitoring and control strategy for automatic detection of process end point as well as on the machine total surface characterization and local defects identification. The approach is based on a multisensory polishing arm allowing measurement of Acoustic Emission and process forces and a scattered light sensor mounted on the machine. The multisensory approach was experimentally validated in polishing with bonded abrasives demonstrating its suitability for process control in RAP.

Industrial characterization of nano-scale roughness on polished surfaces

We report a correlation between the scattering value "$Aq$" and the ISO standardized roughness parameter $Rq$. The $Aq$ value is a measure for surface smoothness, and can easily be determined from an optical scattering measurement. The correlation equation extrapolates the $Aq$ value from a narrow measurement range of $\pm 16^\circ$ from specular to a broader range of $\pm 80^\circ$, corresponding to spatial surface wavelengths of 0.8 $\mu m$ to 25 $\mu m$, and converts the $Aq$ value to the $Rq$ value for the surface. Furthermore, we present an investigation of the changes in scattering intensities, when a surface is covered with a thin liquid film. It is shown that the changes in the angular scattering intensities can be compensated for the liquid film, using empirically determined relations. This allows a restoration of the "true" scattering intensities which would be measured from a corresponding clean surface. The compensated scattering intensities provide $Aq$ values within $5.7 \% \pm 6.1 \%$ compared to the measurements on clean surfaces.
Real time power consumption monitoring for energy efficiency analysis in micro EDM milling

Sustainability has become a major concern in many countries and is leading to strict regulations regarding the impact of products and services during their manufacturing, use, and disposal. Power consumption monitoring in manufacturing companies can lead to a reduction of machine tools energy wastes and consequently to lower expenses. To this end, a complete transparency of energy usage among the entire manufacturing facilities is required. Despite the small volume of material processed, micro manufacturing processes are energy intensive and the optimization of energy usage becomes critical for manufacturing sustainability. Electrical discharge machining (EDM) is considered an attractive solution for the manufacturing of microcomponents. In this paper, a low cost and modular data acquisition system, based on open-hardware and open-source software, for online energy consumption monitoring, is presented. The system described is applied for energy efficiency analysis of the micro EDM milling process by using a state of the art commercial machine tool. A number of sensors is connected to the data acquisition system to measure the energy consumption of the main sub-systems of the machine tool, data is recorded through a microcontroller, and sent to the main computer via Wi-Fi for data storage and analysis. Results show that the process efficiency depends on machine parameters but it is always far below 0.01 %. Solutions are suggested to improve the energy efficiency of the machine tool considered in this work.

Towards development of a novel online tool wear compensation method for dry micro-electrical discharge milling

Towards development of a novel online tool wear compensation method for dry micro-electrical discharge milling

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Assessment of injection moulded nano-patterned surfaces

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Improvement of replication fidelity in injection moulding of nano structures using an induction heating system

In today's industry, applications involving surface patterning with sub-μm scale structures have shown a high interest. The replication of these structures by injection molding leads to special requirements for the mold in order to ensure proper replication and an acceptable cycle time.

A tool insert with functional surface geometry in the sub-micrometer range was produced using aluminum anodization and subsequent nickel electroforming. For the complete replica of the pattern, elevated mold temperatures are required. For this purpose a new mould set-up was developed, which allows rapid heating of the cavity wall by an induction heating system. The capability of the injection molding process to replicate the patterned surfaces into polycarbonate was investigated. Process optimization was carried out in terms of mold temperature/time variation and injection velocity. The replicated surfaces were quantitatively characterized by atomic force microscopy comparing the measurement in the nickel insert with the corresponding polymer nano-features. The experimental results show that the use of the induction heating system is an efficient way to improve the pattern replication.

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Injection molding of nanopatterned surfaces in the sub-micrometer range with induction heating aid

Replication of sub-micrometer structures by injection molding leads to special requirements for the mold in order to ensure proper replica and acceptable cycle time. This paper investigates the applicability of induction heating embedded into the mold for the improvement of nanopattern replication. A tool insert having a surface containing functional geometries in the sub-micrometer range was produced using aluminum anodization and nickel electroplating. In order to provide elevated
mold temperatures necessary for the complete replica of the pattern, a new mold setup was developed, which allows rapid heating of the cavity wall using an induction heating system. Temperature was measured using a thermocouple placed in the mold insert. The system was used to heat up the cavity wall with heating rates of up to 10 K/s. Acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) were used as materials, and heating parameters were investigated after a preliminary optimization with standard heating conditions. The replicated surfaces were quantitatively characterized by atomic force microscopy using specific three-dimensional surface amplitude parameters and qualitatively inspected by scanning electron microscopy. The experimental results show that the use of the induction heating system is an efficient way for improving nanoreplication.

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Integrated Design, an Approach Towards DfµMA

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Micro Injection Molding of Thin Walled Geometries with Induction Heating System
To eliminate defects and improve the quality of molded parts, increasing the mold temperature is one of the applicable solutions. A high mold temperature can increase the path flow of the polymer inside the cavity allowing reduction of the number of injection points, reduction of part thickness and moulding of smaller and more complex geometries. The last two aspects are very important in micro injection molding.

In this paper a new embedded induction heating system is proposed and validated. An experimental investigation was performed based on a test geometry integrating different aspect ratios of small structures. ABS was used as material and different combinations of injection velocity, pressure and mold temperature were tested. The replicated test objects were measured by means of an optical CMM machine. On the basis of the experimental investigation the efficacy of the embedded induction heating system with respect to improvement of replication quality, reduction of injection pressure and
injection velocity as well as reduction of cycle time has been verified.

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The effect of scattered light sensor orientation on roughness measurement of curved polished surfaces
Light scattering is a method for surface roughness measurements well suitable for use in a production environment thanks to its fast measurement rate, insensitivity to vibrations and to small misalignments. The method is however affected by several other factors. In this paper, the effect of angular orientation of a commercial scattered light sensor on roughness measurements of polished cylindrical surfaces with crossed surface lay is investigated to document the robustness of the method.

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Contributors: Pilny, L., Bissacco, G., De Chiffre, L.
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Research: peer-review

The effect of scattered light sensor orientation on roughness measurement of curved polished surfaces
The effect of angular orientation of a scattered light sensor with respect to main curvature and surface lay on roughness measurements is evaluated. A commercial scattered light sensor OS 500-32 from Optosurf GmbH was used. The investigation was performed on polished cylindrical surfaces with crossed surface lay to document the robustness of the method. The instrument area-integrating measuring principle (figure 1) is based on a non-coherent light beam of Ø 0.9 mm and 670 nm wavelength illuminating the measured surface, reflection of the incident light from the surface slopes in spatial directions, and its acquisition within ± 16º angular range with a linear detector array. From the distribution of the acquired scattered light intensity, a number of statistical parameters describing the surface texture are calculated, where the Aq parameter (variance of the scattered light distribution), is used to characterize the surface roughness.

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Validation of in-line surface characterization by light scattering in Robot Assisted Polishing

The suitability of a commercial scattered light sensor for in-line characterization of fine surfaces in the roughness range $Sa$ 1 – 30 nm generated by the Robot Assisted Polishing (RAP) was investigated and validated. A number of surfaces were generated and directly measured with the scattered light sensor on the machine in a shop floor environment. Scattered light roughness measurements of the whole surfaces were performed to investigate the measurement method suitability for 100% quality control. For comparison, the surfaces were measured with reference optical instruments in laboratory conditions. Comparison of the scattered light measurements results taken on the machine with the reference optical roughness measurements taken in laboratory demonstrate the capability of the scattered light sensor for robust in-line surface characterization. This allows for the RAP process control by proper process endpoint detection in a multi-step polishing sequence. The measurements of the whole polished surfaces demonstrate improved reliability of the measurements with fast measurement rate, well suitable for cost-efficient 100% quality assurance.

Acoustic Emission Based In-process Monitoring in Robot Assisted Polishing

The applicability of acoustic emission (AE) measurements for in-process monitoring in the Robot Assisted Polishing (RAP) process was investigated. Surface roughness measurements require interruption of the process, proper surface cleaning and measurements that sometimes necessitate removal of the part from the machine tool. In this study, development of surface roughness during polishing rotational symmetric surfaces by the RAP process was inferred from AE measurements. An AE sensor was placed on a polishing tool, and a cylindrical rod of Vanadis 4E steel having an initial turned surface roughness $Ra = 3.1 \mu m$ was polished using a silicon carbide stone of grit size 600 in 40 polishing passes down to $Ra = 0.07 \mu m$. The polishing task was performed in five steps and after 4, 8, 20, 30, and 40 passes the resulting surface roughness was measured. The results show that with proper AE signal processing, the development of surface roughness in the RAP process can be monitored by AE measurement. The AE based monitoring allows in-process determination of the right moment for changing a polishing tool when applying a given set of parameters is no longer effective to create smoother surface, thus improving the efficiency of the process. It also allows for intelligent process control and generally enhances the robustness and reliability of the automated RAP system in industrial applications.
**Initial verification of an induction heating set-up for injection molding**

Molding of thin and long parts by injection molding leads to special requirements for the mold in order to ensure proper filling and acceptable cycle time. This paper investigates the applicability of embedded induction heating for the improvement of the filling of thin long parts. The object selected for the investigation is a thin spiral.

For the complete molding of the component, elevated mold temperatures are required. For this propose a new injection molding set-up was developed, which allows rapid heating of the cavity wall by an induction heating system. The temperature was measured by two thermocouples placed in the die insert. The system was used to heat up the cavity wall with heating rates of up to 10 °C/s. Experiments were carried out with ABS material. The lengths of the object were measured by a suitable measurement set up.

The experimental result show that the use of the induction heating system process is an efficient way for improving the filling of the cavity.

**General information**

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**Optimization of Grooved Micromixer for Microengineering Technologies**

Due to the absence of turbulent flow and the slow diffusion process, mixing of solutions at micro-scale is a difficult task. This paper describes the optimization route towards the efficient design of a bottom grooved micromixer. Based on thoroughly discussed mixing mechanisms, the optimization was performed using FEM numerical simulations and the starting geometry was a Staggered Herringbone Mixer (SHM) groove design. Optimization procedure consists of two sequences: (I) one SHM groove geometry is optimized based on the magnitude of transversal velocity at the end of the groove and (II) different configurations of six grooves are investigated taking into account capabilities and limitations of microengineering technologies (MET). Newly developed designs were benchmarked against the established SHM design and a better efficiency was achieved. Additionally, a good mixing efficiency was also achieved with a modified Slanted Groove Micromixer (SGM). A SGM prototype was machined by micro electrical discharge milling (EDM) technology. The simulation results were experimentally verified with flow visualization and a good agreement was observed. Due to simple 2.5D geometry and efficient mixing properties the proposed micromixer design is adequate to be used in the Lab-On-A-Chip (LOC) systems.

**General information**

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Contributors: Sabotin, I., Tristo, G., Bissacco, G., Valentincic, J.
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Reliability of electrode wear compensation based on material removal per discharge in micro EDM milling

This paper investigates the reliability of workpiece material removal per discharge (MRD) estimation for application in electrode wear compensation based on workpiece material removal. An experimental investigation involving discharge counting and automatic on the machine measurement of removed material volume was carried out in a range of process parameters settings from fine finishing to roughing. MRD showed a decreasing trend with the progress of the machining operation, reaching stabilization after a number of machined layers. Using the information on MRD and discharge counting, a material removal simulation tool was developed and validated.

An investigation on the effect of surface characteristics on adhesion between polymer melts and replication tools

Understanding interfacial characteristics between a polymer and its associated tool surface is critical to successful optimization of processes such as injection moulding, embossing and extrusion used to produce polymer parts. One of the factors characterizing the strength of the polymer-tool interaction is the adhesion energy and it is specific for a particular polymer-tool pair. Its magnitude depends upon the tool material, tool coating and surface contamination, where relevant, polymer chemical structure, processing conditions and the surface roughness of the tool substrate. This paper presents the results of an experimental study aimed at determining the effect of selected tool surface characteristics on the work of adhesion, by measuring contact angles of polymer droplets on the surfaces. The experimental set-up, selection of test parameters and main challenges faced to date are described and experimental results presented.
A Structured Review and Classification of Demolding Issues and Proven Solutions

The demolding of replicated parts can result in damage to both the replication tooling and finished parts and is a particular problem for the replication of smaller parts which can be quite fragile. Various techniques have been proposed in the literature to solve such problems by reducing the overall demolding force. This paper presents the challenge of demolding replicated parts and reviews the proven solutions from the literature which have been developed. A summary chart of these solutions is presented which may be used to implement plans to solve demolding problems with replicated parts. Such a rationalization of existing knowledge will enable replication tool developers to systematically select and apply proven solutions to solve, and ultimately prevent, demolding problems.

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Contributors: Delaney, K. D., Bissacco, G., Kennedy, D.
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Feasibility of wear compensation in micro EDM milling based on discharge counting and discharge population characterization

This paper investigates the applicability of real time wear compensation in micro EDM milling based on discharge counting and discharge population characterization. Experiments were performed involving discharge counting and tool electrode wear measurement in a wide range of process parameters settings involving different current pulse shapes. A strong correlation is found between average discharge energy of the populations and wear and material removal per discharge. A validation was carried out showing the feasibility of the proposed approach.

General information
Suspension of Water Droplets on Individual Pillars

We report results of extensive experimental and numerical studies on the suspension of water drops deposited on cylindrical pillars having circular and square cross sections and different wettabilities. In the case of circular pillars, the drop contact line is pinned to the whole edge contour until the drop collapses due to the action of gravity. In contrast, on square pillars, the drops are suspended on the four corners and spilling along the vertical walls is observed. We have also studied the ability of the two geometries to sustain drops and found that if we compare pillars with the same characteristic size, the square is more efficient in pinning large volumes, while if we normalize the volumes to pillar areas, the opposite is true.

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An analytical model for force prediction in ball nose micro milling of inclined surfaces

Ball nose micro milling is a key process for the generation of free form surfaces and inclined surfaces often present in mould inserts for micro replication. This paper presents a new cutting force model for ball nose micro milling that is capable of taking into account the effect of the edge radius and the effect of the surface topography due to the previous milling passes. The model is completely analytical can be applied to ball end micro milling of slanted surfaces for any value of the surface inclination angle relative to the tool axis.

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A study of demoulding force prediction applied to periodic mould surface profiles

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Contributors: Kennedy, K., Kennedy, D., Bissacco, G.
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Demoulding force prediction for micro polymer replication: a review of relevant literature

Demoulding components without damage to either the components or tool is critical to successful replication processes. During tooling development designers strive to optimize replication tools to minimize demoulding force and resultant stress on replicated parts. A critical element of this process is an accurate demoulding force prediction model. Various models
have been proposed to predict demoulding forces, each showing limitations in its applicability. This paper reviews existing demoulding force models and parameters affecting demoulding force for micro polymer replication.

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Towards the effective tool wear control in micro-EDM milling
The electrode wear in micro-electrical discharge milling (micro-EDM milling) is one of the main problems to be solved in order to improve machining accuracy. This paper presents an investigation on wear and material removal in micro-EDM milling for selected process parameter combinations typical of rough and finish machining of micro-features in steel. The experiments were performed on state-of-the-art micro-EDM equipment. Based on discharge counting and volume measurements, electrode wear per discharge and material removal per discharge were measured for several energy levels. The influence of the accuracy of volume measurements on the electrode wear per discharge and on the material removal per discharge are discussed, and the issues limiting the applicability of real-time wear sensing in micro-EDM milling are presented.

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Anisotropy of Water Droplets on Single Rectangular Posts
We report results of extensive experimental and numerical studies of the anisotropy of water drops deposited on single rectangular posts of mesoscopic size sculpted on different materials. Drops of different volume deposited on the top face of the posts assume an elongated shape along the post direction. Systematic investigations show that while the angle measured along the direction parallel to the post does not change, the one measured across them increases monotonically with the drop volume. The difference in these two angles is found to be proportional to the contact line eccentricity even for very elongated drops, regardless of the post size and material. Results obtained with the lattice Boltzmann method are consistent with these observations and indicate useful trends on the evolution of the drop shape with the system main parameters. We argue that drops deposited on single posts having a very sharp profile represent an ideal model system to investigate anisotropic wetting.
Realization and characterization of disposable polymer chips for the study of the filling of microchannels at low capillary numbers

A crucial aspect in the use of microfluidic systems is the filling of microchannels with the liquid. In order to better understand this phenomenon, systematic studies of the meniscus dynamics in model system microchannels are being carried out. A critical factor for the reliability of such a study is the capability to control the rounding radius of the micro features used as obstacles. For this purpose a dedicated process chain was developed for the realization of disposable polymer microfluidic chips integrating the desired features and allowing the generation of internal as well as external corners with controlled edge radius. Preliminary test results are presented.

Snapshot of Micro EDM technology for industry

In this paper, the performances and requirements of conventional Electrical Discharge Machining (EDM) and micro EDM technologies are described in order to explore obstacles to the introduction of micro EDM technologies into industrial environment. Special attention is given to machine tool accuracy, machining accuracy, electric pulses, pulse generators and environmental requirements. EDM has been widely used in toolmaking industry to produce dies, moulds and other tools for mass production. It was also found suitable for machining meso and micro structures, since its removal mechanism induces very low machining forces. In particular, a new technology called micro EDM milling, employing milling like strategies, was developed to enable the machining of 3D micro features.

Keyword: Micro EDM milling, Microtechnologies, Pulse generator, Accuracy, Die-sinking EDM
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Tooling Process Chains and Concepts

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Contributors: Hansen, H. N., Arentoft, M., Tang, P. T., Bissacco, G., Tosello, G.
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4M Progress Report 2006-2008

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Direct dynamic calibration of dynamometers for micro milling operations

General information
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Organisations: Department of Mechanical Engineering, Manufacturing Engineering
Contributors: Bissacco, G., Bau, A., Hansen, H. N.
Pages: 500-503
Publication date: 2008
Force analysis in micro milling Al 6082 T6 in various engagement conditions
This paper discusses the issues related to force measurement in micro milling and presents the results of the experimental investigation performed in an on going Cross Divisional Project within the 4M network of Excellence, aiming at force analysis and process characterization in micro milling. Reliable force measurement in micro milling is shown to be a challenging task. Measured forces are affected by contributions coming from the machining system. Based on the performed measurements, tool engagement has been demonstrated to occur at each tooth passing, even at feeds per tooth as low as 2 μm.

High aspect ratio micro tool manufacturing for polymer replication using mu EDM of silicon, selective etching and electroforming
Mass fabrication of polymer micro components with high aspect ratio micro-structures requires high performance micro tools allowing the use of low cost replication processes such as micro injection moulding. In this regard an innovative process chain, based on a combination of micro electrical discharge machining (mu EDM) of a silicon substrate, electroforming and selective etching was used for the manufacturing of a micro tool. The micro tool was employed for polymer replication by means of the injection moulding process.
Modelling the cutting edge radius size effect for force prediction in micro milling

This paper presents a theoretical model for cutting force prediction in micro milling, taking into account the cutting edge radius size effect, the tool run out and the deviation of the chip flow angle from the inclination angle. A parameterization according to the uncut chip thickness to cutting edge radius ratio is used for the parameters involved in the force calculation. The model was verified by means of cutting force measurements in micro milling. The results show good agreement between predicted and measured forces. It is also demonstrated that the use of the Stabler's rule is a reasonable approximation and that micro end mill run out is effectively compensated by the deflections induced by the cutting forces.

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Contributors: Bissacco, G., Hansen, H. N., Jan, S.
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Multidisciplinary graduate course and PhD summerschool in micromechanical system design and manufacture

General information
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Organisations: Manufacturing Engineering, Department of Mechanical Engineering
Contributors: Hansen, H. N., De Grave, A., Bissacco, G.
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Setup of a micro milling force knowledge database - a 4M cross divisional project

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Tooling process chains for polymer replication of micro fluidic devices

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Contributors: De Grave, A., Hansen, H. N., Bissacco, G.
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An uncertainty model for thermal effects on axial depth of cut in micro milling

General information
Publication status: Published
Organisations: Department of Management Engineering
Contributors: Bissacco, G., Hansen, H. N., De Chiffre, L.
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Characterization of pulses in micro EDM milling based on wear and material removal

General information
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Organisations: Department of Management Engineering, University of Ljubljana
Contributors: Bissacco, G., Valentincic, J., Wive, B. D., Hansen, H. N.
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Micro tools manufacturing for polymer replication with high aspect ratio structures using µEDM of silicon, selective etching and electroforming

General information
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Organisations: Department of Management Engineering, Institute for Product Development
Contributors: Tosello, G., Bissacco, G., Tang, P. T., Hansen, H. N., Nielsen, P. C.
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Thermal behaviour of micro EDM milling machine and influence on electrode wear compensation

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Organisations: Department of Management Engineering, Technical University of Denmark
Contributors: Bissacco, G., Hansen, H. N., Wive, B. D.
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A cutting force model for micromilling applications
In micro milling the maximum uncut chip thickness is often smaller than the cutting edge radius. This paper introduces a new cutting force model for ball nose micro milling that is capable of taking into account the effect of the edge radius.

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Organisations: Department of Management Engineering
Contributors: Bissacco, G., Hansen, H. N., De Chiffre, L.
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High–Precise Micro Bonding Process using a Focused Stream of Hot Air
This paper discusses a new approach to adhesive microbonding which can overcome restrictions or drawbacks of the conventional MEMS bonding techniques. The main advantages of this technique are: low process temperature, multi material applicability, partial reversibility and partial biocompatibility. In proposed technique, the adhesive is deposited on the substrate and the micro-component is brought and placed at the requested position. Afterwards, the stream of hot air
is applied in order to soften the glue and to emboss the micropart. After cooling down at room temperature, the glue hardens and final bond is achieved.

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Publication status: Published  
Organisations: Department of Management Engineering, Vienna University of Technology  
Contributors: Andrijasevic, D., Bissacco, G., Giouroudi, I., Smetana, W., Brenner, W.  
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Source ID: 190040  
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2006 – Research › peer-review

**Indirect tooling based on micromilling, electroforming and selective etching**
The tool inserts used for injection moulding or hot-embossing of polymer micro-components, are the most important and expensive and crucial part of this important mass-production process. In this paper a new fabrication scheme is introduce, consisting of a combination of micro-milling, electroforming and selective etching. The basic concept is to exploit the benefit of true 3D-machining in a soft substrate such as aluminium with the excellent replication capabilities of nickel electroforming. The term indirect machining covers the fact that the master that is produced by machining a positive structure, i.e. the opposite of what is needed for the actual mould insert.

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Publication status: Published  
Organisations: Institute for Product Development, Department of Management Engineering, IK4-Tekniker  
Contributors: Tang, P. T., Fugl, J., Uriarte, L., Bissacco, G., Hansen, H. N.  
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Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2006 – Research › peer-review

**Realization and characterization of high precision micro grooves on green ceramic**

**General information**
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Organisations: Department of Management Engineering, Vienna University of Technology  
Contributors: Bissacco, G., Andrijasevic, D., Hansen, H. N.  
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Accuracy of axial depth of cut in micromilling operations - Simplified procedure and uncertainty model

In order to maintain an optimum cutting speed, the reduction of mill diameters requires machine tools with high rotational speed capabilities. A solution to update existing machine tools is the use of high speed attached spindles. Major drawbacks of these attachments are the high thermal expansion and their rapid warming and cooling, which prevent the achievement of a steady state. Several other factors, independent on the tool-workpiece interaction, influence the machining accuracy. The cutting parameter most heavily affected is the axial depth of cut which is the most critical when using micro end mills, due to the easy breakage particularly when milling on hard materials [1]. Typical values for the errors on the control of the axial depth of cut are in the order of 50 microns, while the aimed depth of cut can be as low as 5 microns. The author has developed a machining procedure for optimal control of axial depth of cut in micromilling operations carried out in a workshop environment. Such a procedure is thoroughly described in [1] and [2] and leads to a reduction of the depth of cut error from 36.5 microns to 2.5 microns. Such accuracy has been determined as the result of machining tests. The focus of this investigation is the determination of the uncertainty of the set depth of cut, using the developed procedure, in a range of practical operating conditions and thereby the estimation of the expected accuracy of the method prior to verification of the machined parts.

Geometrical characterization of micro end milling tools

Performance of the milling process is directly affected by the accuracy of tool geometry. Development of methods suitable for dimensional characterization of such tools, with low measurement uncertainties is therefore of relevance. The present article focuses on the geometrical characterization of a flat micro end milling tool with a nominal mill diameter of 200 microns. An experimental investigation was carried out involving two different non-contact systems.
Investigation on a procedure for optimal axial depth of cut accuracy in micromilling
On the basis of a previously developed procedure for control of axial depth of cut in high accuracy micromilling operations, this paper presents an investigation on the estimation of the uncertainty of the set axial depth of cut.

Manufacturing of an injection moulding mould insert with three-dimensional micro features by micromilling
This paper describes the realisation of mould inserts for injection moulding purposes with three-dimensional (3D) micro features using micromilling. The case under consideration was a microfluidic system with regular 2½D patterns as well as true 3D geometries of minimum size 200 µm.

Micromilling of hardened tool steel for mould making applications
The implementation of replication techniques for mass production of micro components relies on the availability of tooling technologies for manufacturing of tools and moulds. Micromilling is a suitable technique for manufacturing of microstructures characterized by high aspect ratios and complex geometries as those characterizing injection moulding moulds. The realization of the micromilling process in connection with hardened tool steel as workpiece material is particularly challenging. The low strength of the miniaturized end mills implies reduction and accurate control of the chip load which requires high positioning accuracy. Size effects, mainly related to the microstructure of the workpiece material and to the limited scalability of tool geometry and surface topography, critically influence the performance of the process in terms of part accuracy, surface roughness, cutting forces and tool wear. This paper presents the micromilling process applied to the manufacturing of micro injection moulding moulds in hardened tool steel, presenting experimental evidence...
and possible solutions to the above-mentioned issues.

**Micro product development methods - how do we focus on the right issues?**

The development of micro and nano products or systems is considered to be a very difficult and challenging task. The manufacturing technologies used are emerging or pushed to the limits of their capabilities. The physical working principle is often not in the same area as common engineering. Moreover, very little knowledge is available outside of the research and development context. Packaging and interaction between micro and macro worlds is one issue that could be specific. But is it actually true that developing a product in this scale framework is very different? The main problem is to focus on the right issues for each required part of the design steps and have the available knowledge and technologies. To that extent, both a technology pushed approach and a product/customer driven approach have to be used in order to conduct to a level of knowledge which can lead to actual production and to bring up a line of future technology research. An analysis of the differences and similarities between macro and micro/nano in topics such as product design, industrial organization, etc. is conducted. The general discussion is supported by case studies of both down-scaled products and products only available at micro scale.

**Precision manufacturing methods of inserts for injection molding of microfluidic systems.**
Wear of micro end mills

This paper addresses the important issue of wear on micro end mills considering relevant metrological tools for its characterization and quantification. Investigation of wear on micro end mills is particularly difficult and no data are available in the literature. Small worn volumes cause large deviations from the ideal micro tool shape, dramatically changing the cutting edge profile as well as rake and clearance angles. This critically affects the performance of the micro tool leading to increased cutting forces and micro tool deflections with detrimental effects on the accuracy of the machined part. For this investigation 200 microns end mills are considered. Visual inspection of the micro tools requires high magnification and depth of focus. 3D reconstruction based on scanning electron microscope (SEM) images and stereo-pair technique is foreseen as a possible method for quantification of wear volume.

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A software tool for simulation of surfaces generated by ball nose end milling

The number of models available for prediction of surface topography is very limited. The main reason is that these models cannot be based on engineering principles like those for elastic deformations. Most knowledge about surface roughness and integrity is empirical and up to now very few mathematical relationships relating surface parameters to cutting conditions are available. Basic models of kinematical roughness, determined by the tool profile and the pattern of relative motions of tool and workpiece, have been so far not reliable. The actual roughness may be more than five times higher due to error motions, unstable built up edge and changing tool profile due to wear [1]. Tool chatter is also affecting surface roughness, but its effect is normally not included in prediction of surface roughness, since machining conditions which generate chatter must be avoided in any case. Finally, reproducibility of experimental results concerning surface roughness requires tight control of all influencing factors, difficult to keep in actual machining workshops. This introduces further complications in surface topography modelling. In the light of these considerations, a simple software tool, for prediction of surface topography of ball nose end milled surfaces, was developed. Such software tool is based on a simplified model of the ideal tool motion and neglects the effects due to run-out, static and dynamic deflections and error motions, but has the merit of generating in output a file in a format readable by a surface processor software (SPIP [2]), for calculation of a number of surface roughness parameters. In the next paragraph a description of the basic features of ball nose end milled surfaces is given, while in paragraph 3 the model is described.
Effect of Cutting Parameters on Microhardness in 2 mm Slot Milling Hardened Tool Steel
This paper presents an experimental study on the dependency of surface integrity on cutting parameters in slot milling of hardened tool steel. A series of 2 mm slot milling tests have been performed with different cutting parameters. Microhardness was chosen for evaluation of subsurface integrity. The process was found to be sensitive to cutting parameters. An increase of feed per tooth or depth of cut produced a reduction of the microhardness of the slot surface. An optimal combination of machining parameters was found to be 80-110 m/min in cutting speed, 0.005 mm in feed per tooth and 0.1 mm in axial depth of cut.

Experimental characterization of micromilled surfaces by large range AFM
Surface generation by ball nose micromilling can be simulated based on technological parameters (ball nose radius, axial and radial depth of cut, feed rate, cutting speed). However, surface 3D topography of such surfaces often widely differs from the simulated one due to the distinctive behaviour of workpiece material, particularly when sub-micrometer chip thicknesses are considered and when machining hard materials. Quantification of surface topography is of fundamental importance for the evaluation of the generated surface; high resolution and wide measuring range being highly desirable for the evaluation of the distinctive behaviour of the ball end mill. The combination of the two demands is to date not matched by any measuring instrument. The paper describes an experimental investigation of surface topography of such micromachined surfaces. Accurate characterization of fine surface details was achieved by the use of an atomic force microscope mounted on a CMM, which takes advantage of the small radius of curvature of its tip. Its limitation on the scanning range is overcome by taking multiple scans and stitching procedures. Other measuring techniques such as, stylus profilometry, optical profilometry and scanning electron microscopy are used for comparison.

Improving axial depth of cut accuracy in micromilling
In order to maintain an optimum cutting speed, the reduction of mill diameters requires machine tools with high rotational speed capabilities. A solution to update existing machine tools is the use of high speed attached spindles. Major drawbacks of these attachments are the high thermal expansion and their rapid warming and cooling, which prevent the
achievement of a steady state. Several other factors, independent on the tool-workpiece interaction, influence the machining accuracy. The cutting parameter most heavily affected is the axial depth of cut which is the most critical when using micro end mills, due to the easy breakage particularly when milling on hard materials. Typical values for the errors on the control of the axial depth of cut are in the order of 50 microns [1], [2], while the aimed depth of cut can be as low as 5 microns. As a result, micromilling cannot enter yet normal workshops provided with conventional milling machines. This paper presents an investigation aimed at the reduction of the error on the axial depth of cut in micromilling operations, in a workshop environment. A method for tool length correction with sub-micrometer resolution by use of an inductive probe was developed, and a series of tests for isolation and identification of error contributions on the axial depth of cut was carried out. As a result, a procedure for optimal control of axial depth of cut was defined which led to a reduction of the depth of cut error from 36.5 microns to 2.5 microns.

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**Surface Generation and Optimization in Micromilling**
This thesis is aimed at developing the micromilling process, investigating the effects of miniaturization on surface topography as well as workpiece surface accuracy, through experimental investigation and modelling of surface topography and cutting forces. Being the focus on the application of micromilling as tooling technology for replication techniques, the work material selected for the experimental investigations was hardened tool steel. The realization of the micromilling process was achieved with a conventional 3 axis milling centre, provided with a high speed attached spindle. The use of such equipment, in connection with micro end mills of 200 μm in diameter, required the development of a method for optimal control of the axial depth of cut. Size effects on surface topography were investigated through experimental investigation and comparison with reference models, developed and validated for milling at conventional size. The non perfect scalability of surface topography was verified. The non perfect scalability of the tool geometry affects the cutting forces. Particularly the cutting edge radius is not downscaled with the same scaling factor as the diameter. Such size effect was effectively modelled and included in an original cutting force model for ball nose end milling. A modification of existing theory for modelling of cutting forces is then proposed, in order to take into account the actual geometry of the cutting process at micro scale. A number of measurement techniques for geometrical characterization of micro end mills have been considered. The limitations of conventional measuring instruments, as optical CMMs, have been demonstrated. Measurements based on 3D SEM images are seen as a forthcoming possibility. The capabilities of the process were verified by manufacturing an injection moulding mould insert with micro features. The satisfactory accuracy achieved indicates that micromilling can effectively be used as a tooling technology in the process chain for micro injection moulding.

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Accuracy of depth of cut in micro milling operations

In any kind of conventional machining operation, dimensional and geometrical accuracy of the machined part cannot be achieved without a precise control of cutting parameters as well as positioning accuracy. Miniaturization of components implies a reduction of all component's dimensions and involves downscaling of conventional manufacturing technologies. Although in micro manufacturing operations particular precautions are taken, the ratio between tolerances and absolute dimensions increases. However, the absolute required accuracy for the functionality increases, therefore the absolute value of tolerances decreases. Existing machine tools designed for conventional size machining operations are generally unsuited for mechanical micromachining due to a too low positioning accuracy and too high thermal deformations of the machine structure (while static and dynamic stiffness is not generally a problem since the magnitude of the cutting forces involved is reduced), which make mechanical micromachining by use of miniaturized tools troublesome or even impossible. This study deals with the use of a conventional 3 axis vertical milling machine equipped with a high speed attached spindle for micro milling operations, the identification of the main sources of inaccuracy and the solutions adopted for the optimization of machine performances through elimination or compensation of such inaccuracies.

Micromilling experiments on hardened tool steel and Titanium

This document is an organized collection of the final settings, decisions, variations and relevant notes regarding the experimental work carried on at Pinol A/S by Giuliano Bissacco within the Ph.D. project Surface Generation and Optimization in Micromilling. The document is divided into sections and subsections according with the natural subdivision of the experimental work. Thus the first section collects general notes, which affect and are common to all the experiments, the second section regards the experiment 1 dealing with flat end milling and the third section regards the experiment 2 dealing with ball nose end milling.

On machine measurements of electrode wear in micro EDM milling

The electrode wear in micro electrical discharge milling (micro EDM milling) is one of the main problems to be solved in order to improve machining accuracy. Most common, the electrode wear is measured on machine by touching the reference point with the tip of the electrode (Touch method) after machining a certain number of layers. The reduction of the electrode length due to the wear (linear wear) is used to modify the electrode trajectory. A laser scan micrometer (LSM) is implemented on the machine mostly to acquire electrode profiles after dressing of the electrode is applied. It is also an alternative solution to measure the linear and volumetric wear, which in principle should be more accurate compared to the measurements performed by The Touch method. In this paper, the performance of the two systems, namely Touch and LSM, were compared. The experimental results show that the accuracy of the electrode length measurement by the Touch method is enough accurate for the linear wear estimation, but the volumetric wear should be measured by LSM system.
**Practical Metallurgy**

This is the report regarding the activities carried out during the practical metallurgy course concerning material properties and structures and their testing & analysis methods. During the course several aspects of the materials have been considered and different techniques have been analyzed.

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- **Contributors:** Bissacco, G., Deganello, D.
- **Number of pages:** 59
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- **URLs:**
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- **Source:** orbit
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- **Research output:** Book/Report → Report – Annual report year: 2003 → Research

**Literature Survey Concerning State of the Art and Surface Generation in High Speed Milling**

This report constitutes a short description of a literature survey concerning the state of the art and latest achievements on the rather new and powerful technology of high speed milling and its modelling, particularly looking at modelling of the generated surfaces. This task has been conducted in August – December 2001. Only the titles of the selected articles are listed while hard copies of them are placed in a separate report.

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- **Contributors:** Bissacco, G.
- **Number of pages:** 6
- **Publication date:** 2002

**Publication information**
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- **Source:** orbit
- **Source ID:** 62942
- **Research output:** Book/Report → Report – Annual report year: 2002 → Research

**Preliminary Milling Tests on STAVAX ESR 52 HRC using 2 mm carbide tools in the range 20 – 200 m/min**

The opportunity to machine hardened tool steels, as widely demonstrated by many authors, is strictly connected with the high speed machining philosophy, namely that, increasing the cutting speed, the percentage of the generated heat during machining that goes away with the chip, increases as well. This consciousness has opened a new field of investigation in material removal machining operations. This new machining concept can be applied with good results to the manufacturing of dies and molds. In fact, reduced manufacturing lead times and costs can be achieved by machining directly in pre-hardened materials since this eliminates the need to finish machine the component after hardening in order to compensate for the thermal distortions. To be effective, this requires state of the art tooling and high speed cutting conditions. While using state of the art tools is always possible and obviously necessary in order to test the actual
potentials of the present manufacturing solutions, the high speed cutting range can’t always be reached, since it depends not only on the maximum spindle speed of the available machine, but, when dealing with milling, also on the tool diameter. This is obviously a limitation for micromilling which is aimed at using mills of diameters of 0.5 mm and smaller; for instance, with a diameter of 0.2 mm, which is the smallest diameter sold by most of the tool suppliers, and with a maximum spindle speed of 100000 rpm, the achievable cutting speed is 63 m/min. Thus it’s apparent that the majority of the micromilling operations are still carried out using cutting speeds that fall within the conventional range.

Surface Generation Modeling in Ball Nose End Milling: a review of relevant literature
One of the most common metal removal operation used in industry is the milling process. This machining process is well known since the beginning of last century and has experienced, along the years, many improvements of the basic technology, as concerns tools, machine tools, coolants/lubricants, milling strategies and controls. However, most of the times, the selection of the cutting parameters in order to achieve the best result on the manufactured part is still mostly an empirical process, based on the experience of engineers and technicians and very often the parameters first selected have to be adjusted afterwards. Nevertheless, many efforts have been done during the last 50 years in order to realize prediction tools for machining processes and particularly for conventional turning and milling operations. Most of these models aim at prediction of cutting forces tool wear and tool life. However, in the industrial world there is a continuous pressure to increase the efficiency of the machining operations in order to achieve tighter tolerances with lower reject rates; therefore models for prediction of surface texture and geometrical accuracy of the machined parts are also essential and many efforts have been addressed in this direction. Among all the machining operations, ball nose end milling has shown great potentials, particularly in machining of sculptured surfaces with high requirements in terms of surface finish; this is due to the good spatial agreement of the mill shape with the geometry of parts or details having variable curvature.