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# Development of a multisensory arm for process monitoring in robot assisted polishing

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**Abstract**
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.

Sensor, Development, Force, In-process measurement

## 1. Introduction

This research work aims at developing a solution for process monitoring in Robot Assisted Polishing (RAP) process, to enable its robust automation and application to rotationally symmetric and free form part geometries such as tools for metal forming and injection moulding of plastics. In the RAP system (figure 1), developed by the Danish company Strecon A/S, a robot arm carries a polishing module with controlled contact force utilizing oscillating tools (figure 1 right) or rotating tools (not detailed in this work). The system is currently semi-automatic, with no sensor based feedback on part processing. In RAP, a generic part is typically polished in a number of process steps using increasingly finer abrasives. Automatic determination of the optimal time for change of the abrasive media between the polishing steps is necessary to ensure sufficient removal of surface marks from the preceding manufacturing operation, while avoiding excessive material removal. It is therefore necessary to establish in-process product quality monitoring. Since it is not possible or it would be too expensive to measure surface finish of sub-µm level during polishing, indirect monitoring methods have to be established.

Ahn et al. [1, 2] reported that die surface roughness during mechanical polishing can be indirectly estimated from Acoustic Emission (AE) measurements, when an AE sensor is placed on the surface being polished and close to the signal source. Previous study by the authors verified the possibility of indirect monitoring of surface generation through AE measurements in RAP of rotating workpieces, where placement of a wired AE sensor on the part being polished is not feasible [3]. Based on screening experimental tests, friction forces were identified as additional process quantities potentially suitable for indirect monitoring of surface generation during RAP. Due to the majority of RAP polished part geometries represented by rotating surfaces, where placement of wired sensors on the workpiece being polished is not possible, suitable sensors have to be implemented directly on a polishing arm.

The objective of this research work is to develop a concept of a multisensory polishing arm allowing measurement of AE and process forces and to verify the reliability of force measurements for process monitoring in RAP.

**Figure 1.** STRECON's Robot Assisted Polishing (RAP) machine tool (left), working space with polishing module utilizing oscillating tool (right).

## 2. Arm development

In RAP, reaction forces in three orthogonal directions $F_z$ (controlled contact force), $F_x$ (friction force in tool oscillation direction) and $F_y$ (friction force orthogonal to $F_x$ and $F_z$, i.e. in workpiece rotation direction) arise from the tool-workpiece interaction, as depicted in figure 2c. $F_z$ is controlled by an air pressure system in the range of 0 N ÷ 25 N. The ranges of friction forces $F_x$ and $F_y$ were not known a priori. Based on screening experiments, the range of $F_y$ was observed of at about 50 % of $F_z$ in RAP of rotating workpieces and insignificant in polishing stationary workpieces. The range of $F_x$ was observed of at about 20 % of $F_z$. To enable measurement of the process forces of the observed ranges, a three component force sensor based on resistive strain gauges was developed. To ensure required measurement accuracy, the arm design was optimized with respect to geometry and material, type, bridge configuration and location of the strain gauges and measurement accuracy of DAQ intended for implementation in RAP. DAQ module NI 9237 from National Instruments was selected for conditioning and acquisition of the strain gauge signals. An iterative design process resulted in the use of metallic strain gauges in half bridge configuration for measurement of bending forces *Fy* and *Fz*. Semiconductor strain gauges in full bridge configuration were necessary to ensure required measured accuracy of *Fx* due to the low strain in compression direction arising from the application of the process forces. The strain gauges were positioned close to the tool holder (application of forces), to ensure maximal signal to noise ratio and to minimize cross-talk in *Fx* from bending directions that could overload the range of the DAQ module. The arm was made in plastic material (PEEK) and a photograph of the manufactured arm is shown in figure 2b.

The force sensor was subsequently calibrated by means of static application of defined loads in the range of application forces with a safety factor of two.

For AE measurements, a miniature (ø 5.5 mm × 10 mm) AE sensor M304A with in-built signal preamplifier from Fuji Ceramics Corporation was implemented in an optimized polishing tool holder (figure 2a). The geometry and material of the tool holder was optimized to ensure good transition path of AE waves from the signal source (abrasive-workpiece contact zone) to the sensor. Placing the sensor in a bore with EDM polished flat bottom surface protects the sensor–to–structure interface from severe ambient conditions and mechanical damage during polishing, ensuring adequate and constant acoustic coupling between the sensor and the tool holder. A compression mount is used to ensure constant and sufficient clamping force of the sensor to supress any air trapping in the interface that may cause significant signal attenuation.

### 3. Dynamic performance verification

Characterization of dynamic performance of the developed force sensor was performed in a number of polishing tests, on the setup shown in figure 2c, allowing direct comparison of the arm measurements with those from calibrated three component piezoelectric dynamometer 9347C from Kistler. The investigations were performed in two configurations, with stationary and rotating workpiece held in a spindle of a CNC machine tool. Different tools (stone, diamond paste with conformable pad) and process parameters (*Fz* of 10 N and 20 N, tool oscillation 1000 $min^{-1}$ to 3000 $min^{-1}$) were used. At high oscillation rates, inertia due to the mass of the oscillating arm affects measurements of *Fx* as shown in figure 3a (green dashed). Such measurement bias can be effectively corrected by measurement of acceleration, calculation and subtraction of the inertial force component from the measurements (figure 3a red dashed). An average measurement error of 1 % in paste polishing and 4 % in stone polishing was observed for the investigated process settings. The results have demonstrated reliable trends in the signals measured by the arm, as shown in figures 3b and 3c for *Fy* and *Fz* respectively, acquired during stone polishing of a rotating workpiece. This is fundamental for the intended process control to be based on the relative change in friction forces, presumably reflecting the change in surface topography during polishing. This is expected to enable in-process automatic detection of the optimal time to change the abrasive media between two process steps.

### 4. Conclusion

A custom designed multisensory arm enabling measurements of AE and process forces in all RAP configurations (i.e. stationary and rotating workpieces) was developed. The force sensor was calibrated and its dynamic performance was verified through comparison with measurements by a calibrated piezoelectric dynamometer. At high oscillation frequencies of the arm, *Fx* measurement is affected by the inertia. Such measurement bias is effectively corrected by measurement of acceleration, calculation and subtraction of the inertial force component from the measurements. The results thereby verify the reliability of the arm force measurements for process monitoring in RAP.

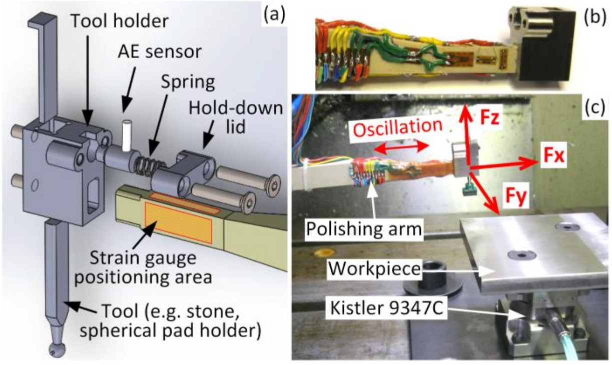


**Figure 2.** CAD model of the polishing arm with integrated sensors (a), manufactured arm (b), setup of dynamic performance verification (c).

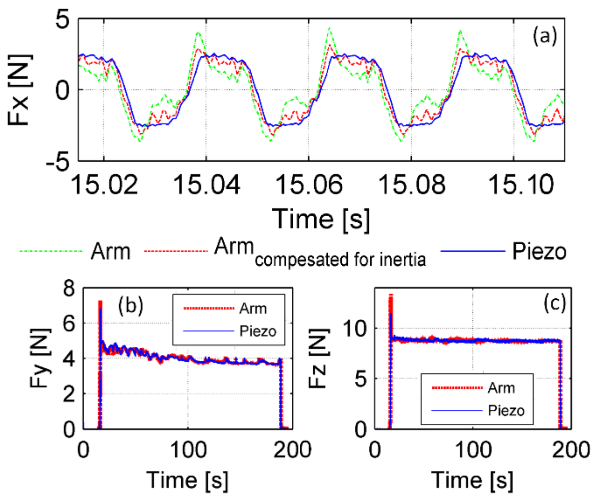


**Figure 3.** The effect of inertia on *Fx* force measurements during arm oscillation 3 000 $min^{-1}$ (a), comparison of forces measured by the arm and reference piezoelectric dynamometer during RAP of a rotating workpiece: *Fy* (b) and *Fz* (c).

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