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Novel Piezoelectric Sensor by Aerosol Jet Printing in Industry 4.0

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***Abstract*—In the latest years, Industry 4.0 paradigm is leading to a reduction of industrial process tolerances, an increase in machine lifetime and an improvement of the quality of the products. The fundamental concept of this fourth industrial revolution is the data coming from the whole production process. Information is usually extracted by algorithms that work on a large amount of data that are collected on the field by a huge set of sensors. New, customized and cheap sensors that are integrated into objects and processes are required. In this work, we propose a method that allows producing a novel class of piezoelectric force sensors through an additive and novel printing method: Aerosol Jet Printing. This technology allows fabricating electronic components and sensors on a wide set of substrates also directly on the surface of the objects. Therefore, smart objects for Industry 4.0 can be designed and manufactured. With the proposed approach it was possible to fabricate both axial and shear force sensors with a d33 up to 101 nC·N^{-1} with a capacitance of 10.4 pF. The fabricated sensors are approximately 300μm thick and can be shaped to fit different custom application requirements.**

***Index Terms*—sensors, piezoelectric, PZT, Aerosol Jet Printing, AJP, Industry 4.0**

I. INTRODUCTION

According to Industry 4.0 paradigm, each machine should be connected, not only to control the process in an inexpensive way but also to provide new features, such as advanced diagnostic and predictive maintenance that could improve the quality of the products and reduce production costs [1], [2]. The key concept of Industry 4.0 is data and how they can be extracted, elaborated and lastly used to improve the production chain preventing machine failures, reducing products tolerances and improving throughput. To obtain data from the industrial environment many sensors can be used to monitor the production parameters; even if different commercial sensors exists, a revolutionary step was made when the industrial tools and objects started embedding sensors that could be application specific. To provide this opportunity, in recent years new sensor production techniques are investigated and, among them, all the printed technologies are arising. With printed technology, we usually refer to a whole class of additive processes that can deposit ink on a substrate in a precise way according to a Computer-Aided Drafting (CAD) project. Screen printing [3], inkjet printing [4] and Aerosol Jet Printing (AJP) are extensively used to fabricated printed sensors and electronics [5]. The screenprinting process transfers an ink through a masked screen onto a substrate. This process is widely used because its equipment is cheap and it can be also implemented in the industry as a roll-to-roll process [6]. The spatial resolution that can be achieved is usually 100 µm, but thanks to some optimization it can be lowered down to 50 µm. Another well-known printing process is inkjet printing that, unlike the previous one, allows a maskless patterning. This process has a resolution similar to the previous one, but the spacing between neighboring lines is affected by several variables that allow achieving a spacing down to 10 µm through a high level of optimization [7]. This technology is cheap, but it can be used with inks within a small range of viscosity and it has many issues about the nozzle that often clogs. A novel technology for printed electronics is Aerosol Jet Printing. Like inkjet printing, it does not require any masks, but it can be controlled directly by a CAD device. This technique allows us to achieve a line width from 10 µm up to millimeters and it also allows us to achieve a conformal printing on non-planar substrates [8], permitting to design and manufacture sensors and electronics directly on the surface of the object. It can also use inks with viscosity from 1 cP to

1000 cP permitting to use a wide range of inks. In this paper, we present how the AJP technique can be used to develop a set of custom piezoelectric force sensors able to sense on the axial and the shear direction. In Section II, the used materials and the manufacturing process are discussed, while in Section III we present and discuss the preliminary experimental results.

II. MATERIALS AND METHODS

In this section the sensors' production process is described, including the chosen materials and the geometries (Section II-A), the printing process (Section II-B) and the polarization of the piezoelectric layer (Section II-C).

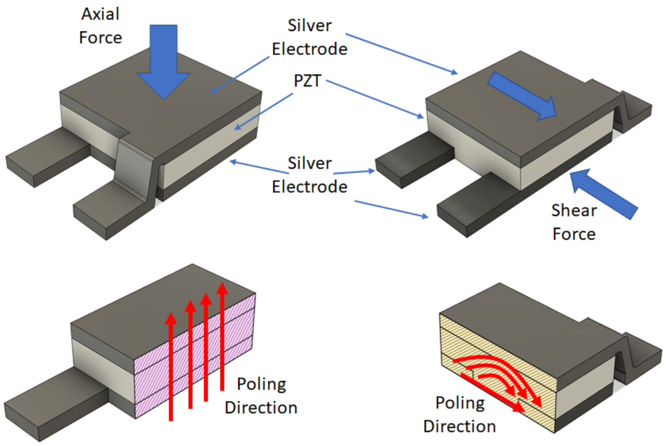
A. Materials and Geometry

Ferroelectric polycrystalline materials were selected because they can be easily purchased in powder form and used to make inks of different properties. Then, they can be deposited on different substrates and then polarized later. Among all the possibilities we started investigating lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$, PZT) and bismuth titanate ($Bi_{12}TiO_{20}$). The former is a well-known class of piezoelectric materials with high piezoelectric sensitivity ($d_{33} > 350\,\mathrm{pC\,N^{-1}}$), while the latter presents moderate piezoelectric coefficients ($10\,\mathrm{pC\,N^{-1}} < d_{33} < 55\,\mathrm{pC\,N^{-1}}$ but a high Curie point that allows using this material also on a wide range of temperatures. In this preliminary analysis, we chose PZT to achieve better electrical responses. In the future, the possibility of using bismuth titanate for high-temperature applications will be investigated. To print the desired materials through AJP, a custom ink was prepared. The ink is based on APC 850 PZT powder produced by APC - American Piezo. Two different solvents were added to the PZT powder: deionized water (DI) and ethylene glycol (EG). To ease the powder's dispersion a dispersant DisperBYK-180 was also added with polyvinylpyrrolidone (PVP) to improve the ink adhesion onto the substrate. The adopted recipe is shown in Table I.

In order to produce a stable and uniform piezoelectric layer, this ink needs a curing process that heats the material up to 1000 °C. According to these requirements, alumina substrates (also known as aluminum oxide Al_2O_3) were used as preliminary substrates for their melting point higher than 2000 °C.

TABLE I: PZT ink composition

	weight %
PZT APC 850	30.0
EG	12.4
DI	49.6
BYK-180	5.0
PVP	3.0



(a) (b)

Fig. 1: Geometry design of the axial (a) and shear (b) force sensors with an explication about the poling principle.

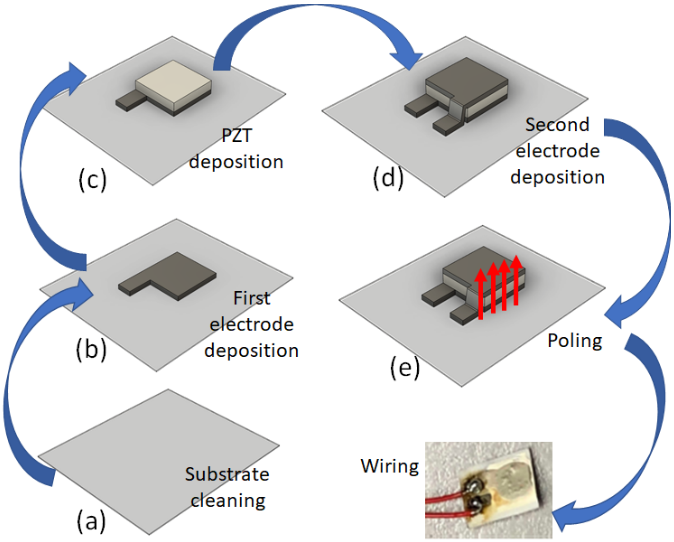


Fig. 2: Production process steps.

Two different devices with two different geometries were designed and fabricated to be sensitive to axial forces or shear forces (Fig. 1). The axial-force sensor has two stacked electrodes separated by a piezoelectric layer. The electrodes are 3 mm side squares. The shear force sensors have two parallel bottom electrodes spaced at 1.2 mm and the piezoelectric ink is deposed in the middle of them. These two bottom electrodes are used for the polarization and after that electrically-shorted. A third electrode is deposed on top of the PZT layer, as depicted in Fig.1b. Therefore, as regards the axial sensor, the polarization is perpendicular to the substrate plane, while for the shear the polarization presents an angle. This is due to the chosen electrodes disposition and it can be seen in Fig.1b. In this way, a component of the axial force can be projected on one of the sensitive directions of the piezoelectric material and thus the sensor acquires sensitivity to shear forces.

B. Manufacturing Process

The manufacturing process is similar for all the implemented devices and it is summarized in Fig. 2.

At first, the substrate was cleaned and then the first electrode was printed using a silver-palladium paste produced by

Hereaus. After this deposition, we applied a two-step curing process. At first, the device was dried at $150\,^{\circ}\mathrm{C}$ for 10 minutes and then it was sintered in an infrared oven at $950\,^{\circ}\mathrm{C}$ for 30 minutes. Then, the piezoelectric ink was printed on the active area. For this custom ink the wide nozzle (Fig.3) head with a $750\,\mu\mathrm{m}$ aperture was chosen to print wide lines and cover the desired area with a double serpentine printing. For this deposition process, a pneumatic nebulizer was selected to atomize the ink and the virtual impactator (VI) was mounted after it. The deposition should be controlled by different parameters that allow achieving line size, process speed and ink adhesion. The chosen configuration that allowed us to achieve a uniform printing layer was obtained setting the sheath gas flow (helps to focus the ink flow and prevents clogging) to $60\,\mathrm{SCCM}$, an exhaust flow (it reduces the flow impacting on the substrate) to $600\,\mathrm{SCCM}$ and an atomizer flow (it atomizes the material) to $800\,\mathrm{SCCM}$. To further control the deposition we tried different deposition speeds; this parameter set the speed of the head on the substrate and thus the amount of material that is deposed, and it defines the process time. To achieve a compromise between the printing process time and the line thickness a process speed of $4\,\mathrm{mm\,s^{-1}}$ was selected. To improve the adhesion between the ink and the substrate, the substrate was preheated to $40\,^{\circ}\mathrm{C}$ to aid the primary solvent evaporation. This deposition process was repeated two times before the following-described curing process. After the depositions, the piezoelectric ink was dried in the oven at $200\,^{\circ}\mathrm{C}$ for 2 hours and then cured in an IR oven at $850\,^{\circ}\mathrm{C}$ for 60 minutes. The depositions and curing of the piezoelectric material were repeated ten different times to increase the film thickness and achieve a $100\,\mu\mathrm{m}$ thick film. At the end of the manufacturing process, the second electrode was printed on top of the piezoelectric material and cured as described for the first electrode. Finally, sensor terminals were then soldered to copper wires.

C. Device Polarization

After the manufacturing process, the piezoelectric films were polarized to orient the ferroelectric domains and thus increase the piezoelectric effect of the films. A high polarizing voltage $V_{POL} = 500\,\mathrm{V}$ was applied across the sensors through the electrodes while the sensors are placed in an oven at a temperature close to half the curie point ($T_{POL} = 150\,^{\circ}\mathrm{C}$) for 30 minutes. Then the oven was switched off and cooled down while the polarizing voltage is maintained for 40 minutes more to impose the direction of the ferroelectric domain. The resulting polarization is different for the two sensors as shown in Fig. 1.

III. RESULTS

The manufactured sensors were tested and characterized to evaluate the process reliability. 12 axial and 4 shear sensors were tested. At first, the sensors were evaluated with a profilometer (Filmetrics, Profilm3D) to get the device total thickness. The results of this first investigation showed that the sensors are $(270 \pm 26)\,\mu\mathrm{m}$ thick on average. These measurements include also $100\,\mu\mathrm{m}$ of the piezoelectric layer.

A. Impulse Stimulation

A high-impedance oscilloscope was used to monitor the electrical response to a mechanical impulse stimulation. A single instantaneous stimulus of force was applied manually, dropping a round tip metal cylinder of about 10 grams onto the sensor surface and the correlated electrical response was acquired by the oscilloscope; one acquisition is shown in Fig.4. These measurements permit to quantify the sensor output in terms of energy generated. Furthermore, it is important to notice that the signal shows a damped oscillation typical of piezoelectric sensors and this can provide proof of the correct realization of the layer.

B. Piezoelectric Coefficients Evaluation

The measurement of the piezoelectric coefficients is crucial to quantify the performances of piezoelectric sensors. Indeed, the piezoelectric coefficients compose a 6×3 matrix that expresses the relationship between the stress $\underline{T}$ applied on the material and the resulting polarization vector $\underline{D}$. Each coefficient expresses the component of the polarization on one axis due to one of the six (three axial and three shear) stress components. d_{33} coefficient allows to characterized the proposed axial sensors because it expresses the polarization generated by a stimulus parallel to the polarization direction. HAN Tech Piezoelectric d_{33} meter YE2730 was used to evaluate this parameter. This device applies controlled stress to the sample and it incorporates a measurement system that reads the charge that is generated on the sample surface (Fig. 5). The results highlighted that all the axial sensors were functioning and provided a mean value for d_{33} of $65\,\mathrm{pC\,N^{-1}}$ with a maximum value of $101\,\mathrm{pC\,N^{-1}}$. This value compared to the one declared by the original piezoelectric powder datasheet ($d_{33} = 400\,\mathrm{pC\,N^{-1}}$) is lower due to the different production process. Moreover, it was possible to observe a considerable dispersion of the values with a standard deviation σ_{dAX} of the samples of $21\,\mathrm{pC\,N^{-1}}$. This could probably be lowered by improving and optimizing both the deposition and the polarization process, that could be done by controlling better all the process parameters. As regards the shear force sensors, the main piezoelectric coefficient that is considered is d_{15} that expresses the polarization on electrodes due to shear stress applied. The experimental setup includes the YE2730 meter described before, but we glued on top of our sensors another alumina layer that was used to apply the desired stress. According to these measurements, the shear force sensors are less sensitive to the applied force presenting a mean d_{15} of $5.5\,\mathrm{pC\,N^{-1}}$. This result could be improved by changing the polarization process, but it works as a proof of concept that it is possible to manufacture even piezoelectric shear sensors and polarize the sensors directly on the substrate of the object. As regards the production variability we calculated a standard deviation σ_{dSH} of $1.6\,\mathrm{pC\,N^{-1}}$. Even if this value seems to be much better than the one measured for the axial sensors there

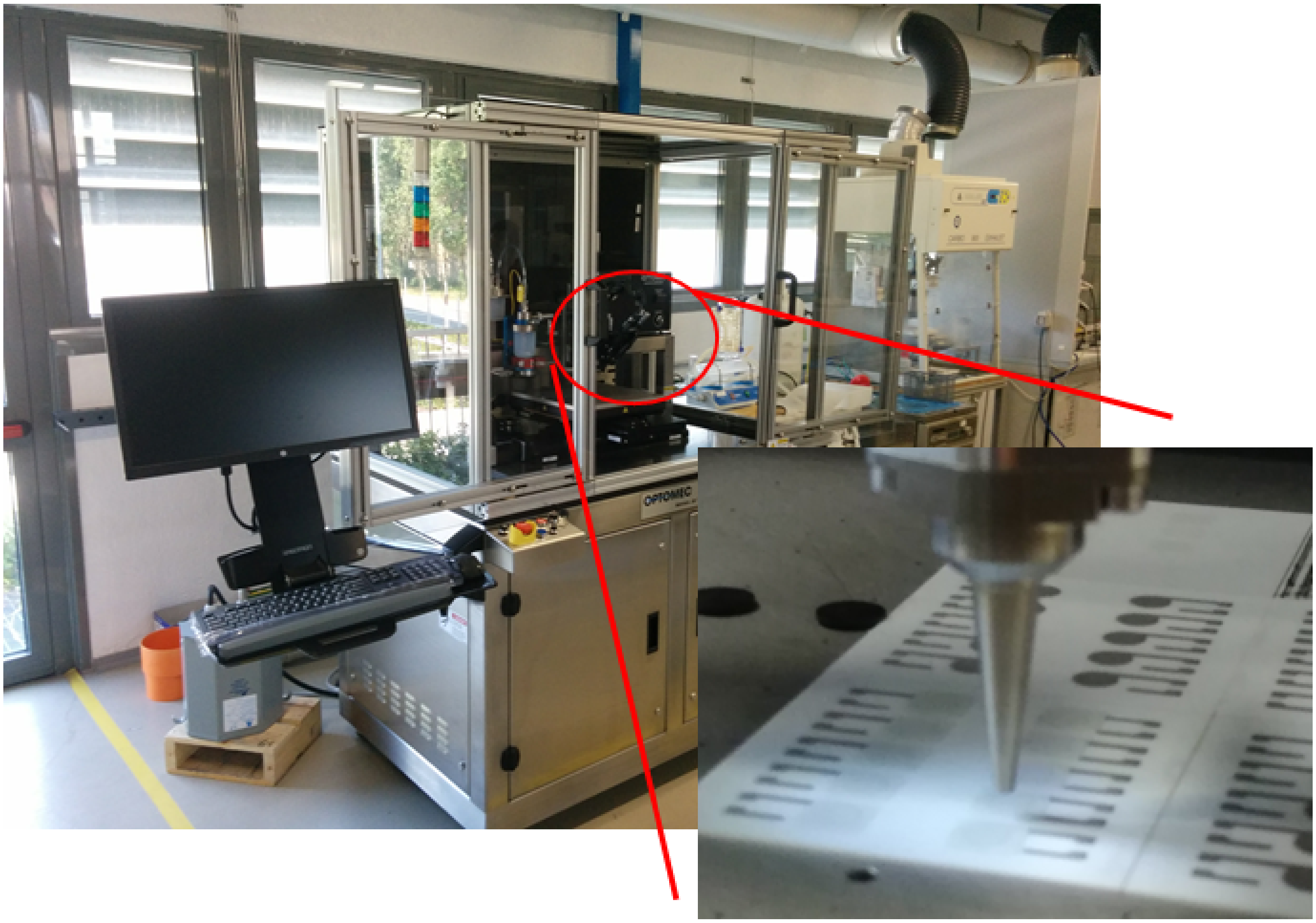


Fig. 3: AJP machine with a detail of the wide nozzle.

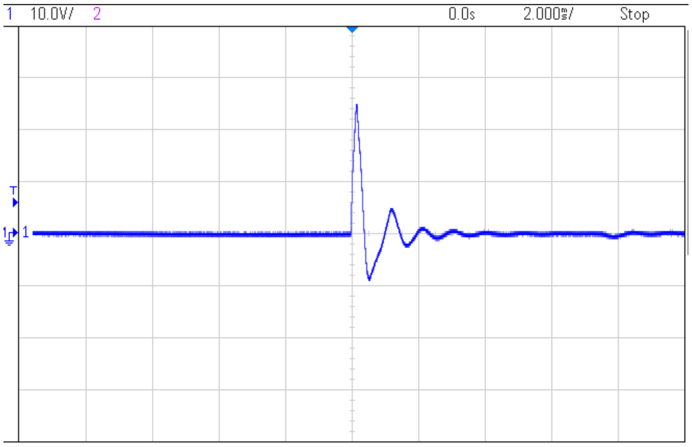


Fig. 4: Typical electrical response of a printed axial force sensor stimulated with a single pulse.

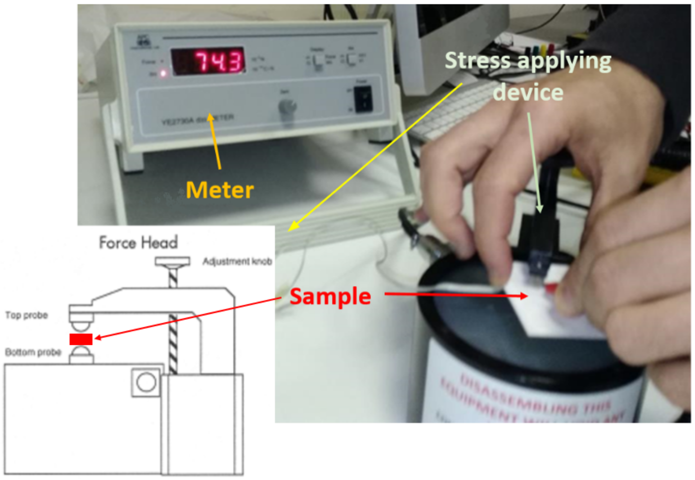


Fig. 5: Experimental setup for measuring d$_{33}$.

exists a huge difference between the two mean values. If we evaluate the coefficient of variation instead of the standard deviation for the two groups of sensors we get $c_{v_{dAX}} = 0.33$ for the axial sensors and $c_{v_{dSH}} = 0.29$ for the shear ones demonstrating that the process variations are similar for both of the sensors.

C. Electric Capacitance Evaluation

Agilent HP 4194a Impedance/Gain-Phase Analyzer was employed to evaluate electrical capacitance. For the axial sensors, $(14.9 \pm 6.0)\,\mathrm{pF}$ was on average obtained. Similarly, the electrical capacitance of the shear sensors is $1.8\,\mathrm{pF}$ on average, with a standard deviation of $0.5\,\mathrm{pF}$. For the axial sensors the resulting coefficient of variation is $c_{v_{cAX}} = 0.40$, while for the shear sensors the repeatability is better with a coefficient of variation of $c_{v_{cAX}} = 0.27$.

IV. DISCUSSION AND CONCLUSIONS

In this paper, piezoelectric force sensors were designed, fabricated and tested. The sensors were manufactured through a fully additive and cheap technology: Aerosol Jet Printing. This technique can depose in a controlled manner an ink both on planar or 3D surfaces and thus is promising to quickly produce custom sensors on a wide set of substrates. These sensors can be fabricated directly on the object surface, customized for a specific application. This will lead to design of new smart objects able to control the process in an inexpensive way, but also to provide new features, such as advanced diagnostic and predictive maintenance, for improving the quality of the products and for improving production costs. In this work, we explored the proprieties of lead zirconate titanate as a piezoelectric material and we proposed a technique to deposit the piezoelectric ink through AJP on alumina. The proposed process was successfully adopted to easily fabricate both axial and shear force sensors. For the axial sensors the average d_{33} is $65\,\mathrm{pC\,N^{-1}}$, whereas for the shear sensors the average d_{15} is $5.5\,\mathrm{pC\,N^{-1}}$. The achieved piezoelectric coefficients are lower than the ones provided form the material datasheet. Even if some improvements were made, some other optimizations can be made to increase the piezoelectric coefficients and reduce the variability of the parameters of the sensor. We are still investigating the use of different piezoelectric inks like bismuth titanate based that, thanks to its higher Curie point, could improve the behavior of the device on a broad range of temperatures. Another interesting possibility empowered by AJP is to print sensors on non-planar or even stretchable substrates. At the moment the fundamental requirement is to use substrates that can stand high curing temperatures, however thanks to new curing processes it is possible to use non-standard and even flexible/stretchable substrates like paper or plastic sheets.

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