Printed sensors produced via thick-film technology for the use in monitoring applications

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1. Introduction

Today sensors have found their way into many different kinds of devices and whole systems. Smartphones, automats, cars and other things of daily life can be mentioned here as well as production machines like industrial robots, presses, printers and more. Increasing complexity of devices or systems and their target specifications lead also to advanced or changing requirements to sensors.
Upcoming requirements for future sensors beneath size, price and performance are multi-functionality or the ease of integration into a device. Thick-film technology and here especially screen-printing offer possibilities to meet these challenges in sensor development. With this printing method powder-filled pastes can be applied on different substrates such as metals (additional insulation if necessary), ceramics or plastic material as well as directly onto a part. After the printing process the sensor structures get their functional properties during a following heat treatment. Advantages of the use of screen-printing as an application method are the high diversity of materials that can be processed, cost efficiency and high throughput rates combined with a structure width down to 100 μm. Another aspect is the possibility of printing a combination of different sensors onto the same substrate or part.

2. Experimental details

Substrate materials were alumina and stainless steel sheets. If needed an additional dielectric layer was also screen-printed on the substrates for electrical insulation. Beneath the sheet material also powder metallurgically produced gear wheels were used.

The powder-filled pastes that finally result in the sensor structures consist of a binder system, elemental or pre-alloyed powders and if necessary further additives. Particle sizes of the powders used were in the range of 1-30 μm. Homogenization of the pastes was performed by a 3-roller mill. Screening of the right powders and the composition of the ingredients are some of the critical parameters for the resulting sensor performance.

The application of the pastes was made by screen-printing. A schematic diagram of the process is shown in Fig.1.

The paste was deposited on a screen and then transferred by a flood bar passing over it. This flooding step fills the mesh openings of the screen with paste. In the following printing step a squeegee overcomes the screen pressure to apply the paste onto the substrate. While printing the viscosity of the paste is reduced by velocity and force of the squeegee. This thixotropic behavior of the paste is necessary for a good printability [2]. For each type of sensor one or more screens were used with structure and interspace width of minimum 100μm. Multilayer-printing was performed with accuracies in the range of 2-20μm.

After printing a drying of the structures at 125°C was performed, followed by the functionalization of the sensor structures in a sintering process. Sintering temperatures varied from 750°C to 1300°C with atmospheres were mainly nitrogen and hydrogen, depending on materials used.

The performance of the different thick-film sensors has been evaluated by specific testing methods. Thermocouples were tested on their electrical properties like conductance and test runs in direct comparison with
commercial wire thermocouples were performed. Concerning the magnetic sensor structures for rotational speed and positioning a hall sensor was used for signal detection.

3. Thermocouples

Two types of temperature measuring sensors dominate the market, resistance temperature detectors (RTD, e.g. PT100) and thermocouples. Principle of measurement for RTD is a temperature-sensitive change in resistance of a metallic or semi conductive element, commonly used is platinum. Thermocouples work on the basis of the thermoelectric or Seebeck effect. Two different materials form the legs of the thermocouple which cross at the measuring point (hot junction). On the other end of the legs a temperature specific voltage can then be measured [3].

The development of RTD has changed in the last time from common sensors with glass-encapsulated platinum wires to thin-film elements on ceramic substrates. With regard to thermocouples Fraunhofer IFAM has developed first thick-film thermocouples of different types, like type T (Cu-CuNi), K (Ni-NiCr) or J (Fe-CuNi).

Thermocouples were printed on insulated steel substrates as well as on ceramics with different porosities. Some of the ceramics were also equipped with an adhesion layer. Fig.2 show some of the different substrate variants equipped with two thermocouples pairs. As can be seen the two different materials, here Cu and CuNi overlap in the front of the substrate. Each material was printed in a separate step with a short drying at 125°C in between. Adjustment for the second printing step was made with assistance of a camera and reference marks on the substrates. Thereupon a drying at 125°C for 30 minutes in air was performed. Sintering temperatures varied from 750-900°C for type T (Cu-CuNi) and 1100-1250°C for type K (Ni-NiCr) under nitrogen or hydrogen atmospheres.

Fig. 2. Screen-printed thermocouples of type T (Cu-CuNi) on different substrates (from top: dense alumina with adhesion layer, porous alumina and insulated austenitic steel).

Former investigations [4] revealed that printed thermocouples of type T (Cu-CuNi) show a linear behavior for rising temperatures up to 180°C. Here the aim was to test the printed thermocouples at even higher temperatures and compare different contacting methods on their influence on the thermocouple’s performance. In every test run a common wire thermocouple of the same type was used for reference reasons. All thermocouples in a test run were connected with corresponding thermocouple wire to a standard multi-channel measuring box for wire thermocouples (MC USB-Temp) which continuously recorded the measurement data. The output data is the temperature; results are temperature - time diagrams. The resulting temperatures were also compared regarding absolute deviations for comparison with literature values.
3.1. Influence of the electrical contacting method

The electrical contact of the manufactured printed thermocouples was made by the following different contacting methods - spot-welding, adhesive bonding and clamping. The resulting temperature - time graph of a comparison test run with screen-printed type K thermocouples (Ni-NiCr) is shown in Fig.3.

![Graph showing temperature vs. measuring time for different contacting methods](image)

Fig. 3. Comparison of screen-printed thermocouples of type K with different electrical contacts up to 120°C (common wire thermocouple was used as reference).

The temperature was increased in steps of 10K from 20°C to 120°C with short dwelling times in between the heating steps. All different contacting methods show a similar measuring curve. Absolute deviations between the differently contacted screen-printed thermocouples were in the range of ±0.1K during the temperature plateaus. Compared with the wire thermocouple the fit during the temperature plateaus is ±0.1K. During the temperature ramps the response characteristic of the screen-printed thermocouples is a bit slower, which can be explained by the higher thermal capacity (because of the ceramic substrate) to be heated of the screen-printed thermocouples and therefore a damped signal.

Concluding it can be mentioned that the different types of electrical contacts have no significant influence on the performance of the printed thermocouples.

3.2. High temperature performance

Another focus of the work was the investigation of the performance of the screen-printed thermocouples at higher temperatures than investigated in former studies. Therefore test runs up to 250°C and 450°C have been performed. Temperature was increased here in steps of 50K from 20°C to 250°C respectively to 450°C in the other test run with short dwelling times in between the heating steps. Fig. 4 shows the resulting temperature - time graph of a test run up to 250°C of two screen-printed and one common wire thermocouples of type K (Ni-NiCr).

The measured temperatures of the screen-printed thermocouples were in good agreement to the common wire thermocouple. The red curve of sample TC-2 is for that reason not visible on the graph as it is covered by the other curves. Absolute deviations were ±1.1K during the temperature plateaus and therefore in the range of tolerances referring to IEC 584 respectively EN 60584 for wire thermocouples.
Fig. 4. Temperature-time graph of screen-printed thermocouples of type K in comparison with common wire thermocouple up to 250°C (red curve of TC-2 is covered by the other curves).

Fig. 5 shows the results of a performed test run up to 450°C. The measurements confirmed the good performance of the screen-printed thermocouples with good agreements of the measured temperatures compared to the reference wire thermocouple. The blue reference curve is therefore partly covered by the other curves. Absolute deviations of ±2.3K were observed. Here again also the difference in thermal capacity has an influence on these values, so that one can state that the average trend lines of all three thermocouples have a better accordance. Nevertheless even the deviation of ±2.3K meet the tolerances of IEC 584 respectively EN 60584.

For this reason the results of former studies concerning the performance of screen-printed thermocouples could be confirmed and enlarged to temperatures up to 450°C. The screen-printed thermocouples show standardized accuracy and are compatible with standard measurement equipment.

Fig. 5. Temperature-time graph of screen-printed thermocouples of type K in comparison with common wire thermocouple up to 450°C (blue curve of wire thermocouple is partly covered by the other curves).
4. Magnetic sensor for rotational speed & position

There are different methods available for measuring of rotational speed and positioning of rotating parts or systems. Mainly used are magnetic, acoustic or optical sensor systems. Here sensor structures of permanent magnetic material (AlNiCo) have been produced by screen-printing that could be detected by a hall sensor after sintering. Simple radial line structures can be used for rotational speed measurement; so-called nonius structures (Fig. 6 left) allow in addition the measurement of angular positioning. It is possible to print the sensor structures either on bulk material sheets (ceramic, stainless steel) or on powder metallurgical parts (Fig. 6 right). Heat treatment was performed according to description in literature [5].

![Screen-printed AlNiCo structure on non-magnetic steel sheet (left) and radial line structure on powder metallurgical gear (right).](image)

To determine the magnetic characteristics of the used material, pressed and heat treated pre-alloyed powder was tested on its magnetic properties. The results showed in comparison to literature values lower performance (65% of coercivity and 35% of remanence). This may be explained by non-reached cooling rates during heat treatment in the test runs in comparison to the literature values, what could have led to an undesired microstructure. And secondly by the lack of a magnetic field during cooling so that an isotropic magnetic arrangement is existent.

To verify the performance of the sensor structures, radial line structures (12 single elements) were printed both upon tubular axles and flat disks, mounted on the front end of the axle. Measurement were performed by Fraunhofer IIS with a hall sensor, rotational speeds were in the range of 60 rpm. As can be seen in Fig. 7, the 12 single elements of the structure can clearly be identified. Measurements of the magnetic performance have revealed values that are high enough for the use of such sensor structures in industrial applications.
5. Conclusion

In summary it can be stated that it is possible to produce common thermocouple types (T, K, J) and permanent magnetic sensor structures via thick-film technology. They can be applied by screen-printing on bulk material as well as on powder metallurgical parts. This allows either to design additional sensors for a system health monitoring or to integrate sensors onto existing parts of a system (e.g. gears, axles).

Screen-printed thermocouples reached standardized tolerances up to temperatures of 450°C. Different electrical contacting methods work with the screen-printed thermocouples. No significant influence of the contacting type on the sensors performance could be revealed. The printed thermocouples provide the same voltage signal and accuracy as wire thermocouples and are fully compatible to the industrial interfaces of controllers and actuators.

Permanent magnetic structures applied by screen-printing could not reach literature values of coercivities and remanences. In performed rotational speed measurements, magnetic performance was nevertheless adequate for being detected by a hall sensor in qualities sufficient for industrial applications.

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