PROJECT FINAL REPORT

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Project acronym: MESMESH

Project title: *Ultra-thin conductive ceramic mesh to monitor stress and wear on a steel surface*

Funding Scheme: Small or Medium-scale focused research project (NMP)

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1. Final publishable summary report

1.1. Executive summary (Publishable)

Today there are no adequate means of measuring the surface damage done to steel surfaces in industrial machinery like drive shaft's, axels, gears, break pads, flanges for fixed drilling and grinding machines, dyes for extrusion or moulds for injection moulding. This means that it is impossible or very difficult to determine when to change a part or perform maintenance.

This results in enormous losses for the European Community due to machines breaking down and causing delays in production and delivery. For validating the technology we have chosen to focus primarily on flanges and moulds for injection moulding due to the relative ease of applying the proposed technology to these application areas.

We have addressed the problem by creating a cheap, innovative ultra thin conductive ceramic mesh to monitor stress and wear on a steel surface, incorporating novel technologies centred on laser etching, conductive ceramic alloys and advanced algorithms capable of detecting wear and tear or damage to a metal surfaces in real time production environments.

The benefits that the MesMesh sensor technology provides are:

- An in-situ structural health monitoring system for steel surfaces subjected to continuous friction to increase end product quality and reduce scrap production by ensuring surfaces on flanges, moulds, dyes are not worn out or damaged.
- A real time structural health monitoring system for steel surfaces to allow the end user to perform preventive maintenance instead of waiting for the machine or tool to break down.
- A measurement system which can continuously or at any particular desired instance monitor a steel surface without physically interrupting the process utilising the steel surface and with negligible preparation time.

Innovative areas of research in the project included

- Utilization of femtosecond laser technology in making microscopic grooves on the steel mesh
- Development of conductive ceramics
- Micromachining holes and notches in the 250 μm diameter ceramic fiber in order to improve the wire bonding
- Development of conductive ceramics

Successfully bonding ultra-thin wires to the ceramic sensor

Additional breakthroughs during the project included

- Utilization of femtosecond laser technology in fiber laser technology
- Utilization of femtosecond laser technology in fibre laser technology
- Development of wear prediction algorithm
- Development of an accurate accelerated wear process
- Extending the thin bonded wires to make them more robust
- Developing a graphical user interface to show the resistance of the ceramic in real time

The overall technological aim was the development of a pre-commercial prototype mould with an in-situ sensor and measurement system to allow continuous structural health monitoring. This aim was fulfilled and the technology has proven to be viable in a commercial environment.

1.2 Summary description of project context and objectives (Publishable)

i. Project context

The proprietary concept devised by Müggler, and upon which the MesMesh proposal is based on the need of increasing production efficiency by increasing machine utilization, increasing quality of manufactured goods and reducing the amount of scrap parts produced. Considering the EU market for manufactured plastic goods (large scale production of batches of 100 000 or more parts) there is a significant environmental impact leading due to the reduction of several thousand tonnes of plastic that would otherwise be disposed by landfill or incineration.

A significant aspect of the proposed technology is that it can easily be adapted to monitor the structural health of complex metal engineering components such as for instance, gears, drive shaft's, axles, break pads and dies for extrusion.

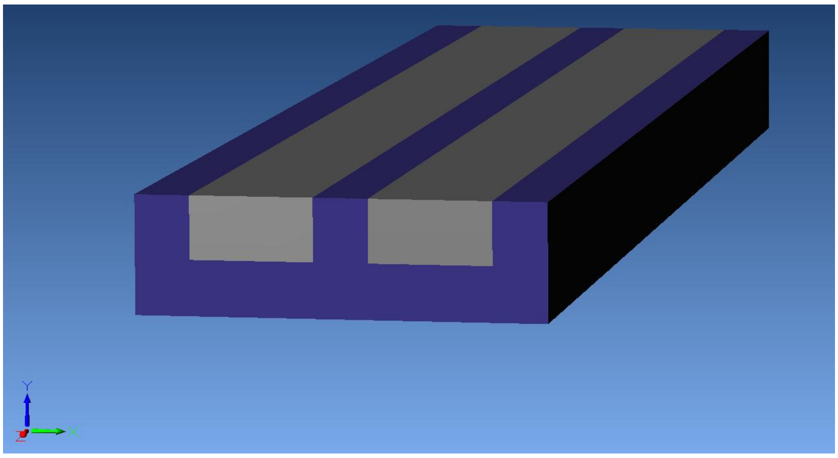
There are no systems on the market capable of performing the measurements needed to give a full overview of the wear, tear and damage done to a metal surface. The best technologies currently available fall short of being effective for the following reasons:

- The current methods are focused only on measuring the strain a surface is subjected to, and they do not measure the actual wear and damage done to the surface;
- The current methods are expensive to embed (particularly optical fibres) and require expensive optical equipment;
- Strain gauges are not large enough to cover the surface of a mould.
- Furthermore It is exceedingly difficult to embed strain gauges or FBGs in a mould and the information obtained would only be strain measurements, which is not a direct indicator of the wear or damage done to the mould;
- The scalability of the SOA is also very limited. Some systems such as electromagnetic systems would require a number of different products to be used with different size moulds. Furthermore most of these are based on indirect measurements, which would give a very poor signal to noise ratio, meaning it would be impossible to make accurate measurements.

ii. Scientific and Technological Objectives

Our overall technological aim is the development of a pre-commercial prototype mould with an in-situ sensor and measurement system to allow continuous structural health monitoring. This system consist of a sensor grid (mesh) incorporated into the outer surface layer of the metal mould. The sensor grid system will be created micromachining a smooth walled, depth controlled grooves in to the metal surface using a femtosecond laser. Into the groove a ceramic is deposited and sintered to form a thin continuous layer. The sensor measurements generated by the sensor grid will be processed by a monitoring device to give the user a real time indicator of the structural health of the metal part.

Figure 1.1 – Cross-section of the Mesh structure



Key – Grey = Ceramic composite, Purple = Metal

Dimensions of ceramic composite– width ≤ 200 µm, depth ≤ 200 µm

Damage and wear of the wave guide material will affect the magnitude and characteristics of a signal passed through it and thus we can determine the onset and extent of damage in the surrounding surface layer of the metal.

The pattern in which the grooves are micro-machined into a mould or other metal surface will be dependent on the specific application, size of mould and user requirements. It is anticipated that in commercial use the mesh will be confined to a few critical areas governed by the application and observed damage mechanisms in the mould.

Our specific scientific objectives are centred in the field of mould modifications:

- Development of predictive models for frequency dependent electrical properties of ceramic composites;
- Understanding of microstructure-property relationships for the frequency dependent properties of conductor-insulator ceramic composites;
- To carry out research work related to ultra-short laser ablation process at different radiation parameters such as wavelength, pulse energy density, repetition rate and spatial pulse shape.

Our detailed technological objectives for individual elements are as follows:

- Electrical characterization of conductive ceramic composites;
- Use of predictive tools for the design of optimum conductive ceramic for the waveguide sensor application;
- Development and embedment of the conductive ceramic for the waveguide application into steel;
- To find optimal process parameters for forming smooth walled and depth-controlled grooves in metal by laser ablation.

Our detailed integration performance objectives are:

- To be able to produce moulds with a laser etched grove with a width and depth of ≤ 200 µm with a deviation of no more than 5%;
- To produce a conductive ceramic with a coefficient of thermal expansion (CTE) of 36 x 10^{-6} K^{-1} (the same as steel) that can be bonded and/or sintered into the laser etched grove to form a mesh;
- To have a software that can interpret the signal responses from the ceramic mesh to provide the end user with a tool to do real time monitoring of the structural health of a given steel surface;
- To ensure that the production costs of the developed technology when applied to a mould will not increase costs by more than 20%. This is considered acceptable as the life expectancy of the mould will be increased by no less than 20% whilst giving the end user benefits of reduced scrap and increased quality.

As per our objectives we developed a novel technology based on state of the art knowledge in both micromachining using Pharos femtosecond lasers and the latest knowledge and insight in the field of conductive ceramic based materials. Combined with cost effective digital signal processing and advanced control algorithms we integrated this into a commercial application that has been tested and had its performance verified.

State of the art and beyond

There were several limitations that needed to be overcome in order to enable us to achieve our focused technological objectives. The technical barriers the MesMesh sensor prototype had to overcome were among others:

- Current methods for laser micromachining are not perfected and optimized to micro machine steel surfaces to sizes of around 200 µm with no more than a 5% deviation;
- Current knowledge on dielectric waveguides with tailored physical properties such as thermal expansion and which are capable of strongly bonding to a steel surface is not sufficient;
- Current bonding methods for transducers to dielectric materials such as ceramics are cumbersome and expensive, and a cheap novel method is needed for commercialization.

At project end the project has included numerous areas where innovative measures and solutions have been developed. This section highlights some of the results achieved and innovative solutions proposed. Details on these items are to be found in the 37th month Technical Progress report and some of the previous technical progress reports.

Laser development - VULRC

- High speed +AC laser testing finalized
- The possibility to machine ceramics
- Innovation: machining of fibres

Ceramic development - Bath University

- Mode of operation developed
- New conductive ceramics developed
- Processing of standard ceramic into materials of known reproducible resistance

Electronics and contacting - MET and Pera

- Proved that microwave demonstration can be used
- Developed monitoring system
- Special algorithm to predict rate of wear developed
- Accurate and repeatable method of accelerated wear testing
- Graphical user interface made
- Wire extension method developed

Integration – Müggler and RTD partners

- Solution found to properly insulating the fibres
- Solution found the wire joining to the fibres
- Solution found regarding insulation of the wires
- Development of the sensor body (modular system)
- New: Inclusion of the reference sensor
- Contact and wiring technology has been developed
- New fibre lasering innovative steps taken

Testing - Matrican and Balpol

- Way to introduce the sensor into the mould
- Identification of the wear points
- Research into the environmental influences
- Placement of the wires in an industrial setting

The sensor integration has been achieved and the necessary technology for the wear sensor has been developed. For further optimization and commercialization of the sensor the MesMesh partners drafted a innovation wishlist at the last meeting of the consortium. This is a summary of ideas of how the sensor could be further developed to fit the need of different sectors or making innovative developments to the existing basic framework of the sensor technology utilized.

In the area of electronics the partners highlighted the need for a modeling study of how the sensor changes with wear and the immediate need of making the technology wireless so it is easier to use on location. Further development and research into fouling – algorithmic development extension to network of sensors. In addition, to making a modeling study of how the resistance of the sensor changes with wear.

In the area of ceramics, Bath University highlighted the idea of making higher resistivity ceramics, developing a standardized process in order for the sensor production to be commercialized, further development of glass insulation, development of an innovative insulated sensor, further developing and optimizing techniques for the contacting and bonding of wires, in addition to the integration of the sensor and signal collection.

In the area of laser technology, VULRC proposed testing the sensor further with higher repetition rate lasers, making further reductions of production time and new research into lasering the fibers. They also proposed an idea of making an integrated system for all required applications.

Other ideas on the innovation wishlish would be to do testing of sensors with different depths, for critical points. One partner proposed an idea of an integrated sensor based on silicone technology and proposed testing of alternative materials such as platinum wires and developing a ceramic sensor body.

Microwave application has also been proven to be a viable solution – but microwave technology in this area is still too expensive for general commercial production. But the area is extremely relevant as the advantage is non-contact which automatically solves the bonding/contacting of the current sensor system. In the future, this application could be a very promising research area.

With regards to alternative applications of the sensor, other than the mould industry, it was suggested that the other applications of the system could make profitable use of the technology:

- Bushes
- Steam pipes
- Brake discs
- Wind turbines
- Steel stamping

The technology for the MesMesh sensor is viable, promising and relevant for many different applications in various industrial sectors. Preventive maintenance is a constant battle for European production companies and the MesMesh technology has the possibility to provide them with an effective tool in the battle against lost production time.

1.3 Description of the main S&T results/foregrounds (Confidential – not to be published)

I. Cutting edge laser technology (VULRC)

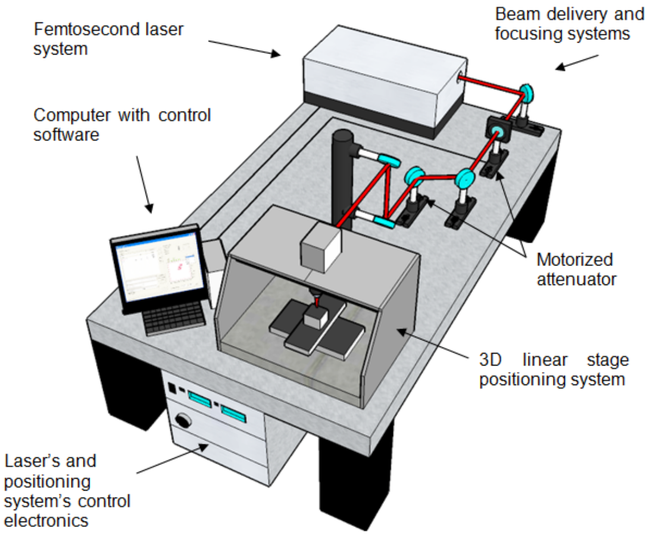
Vilnius University Laser Research Center (VULRC) took part in the Mesmesh project as the main developer of laser micromachining system, capable to cut micro fine grooves on metallic sample surface without any degradation of material's physical and chemical properties. There is a limited choice of technologies suited for such tasks, and the most versatile is the micromachining with femtosecond (<10^{-12} s duration) laser pulses. Lasers offer great freedom for flexibility, degree of automation, they may work without any consumable materials and in a non-contact way. Femtosecond laser ablation, because of the reduced heat-affected zone, where melting and solidification can occur, allows the micromachining and surface patterning of materials with minimal mechanical and thermal deformation and with micrometer precision. Although femtotechnology is still not mature, it is successfully competing in some specific challenging fields of automotive industry, medicine, production of microelectromechanical and microfluidic systems and also consumer electronics. Researchers at VULRC have developed several micromachining systems, researched micro-cutting physics and performed optimization tasks in order to achieve grooves with parameters fully fulfilling MesMesh project needs.

Micromachining strategies

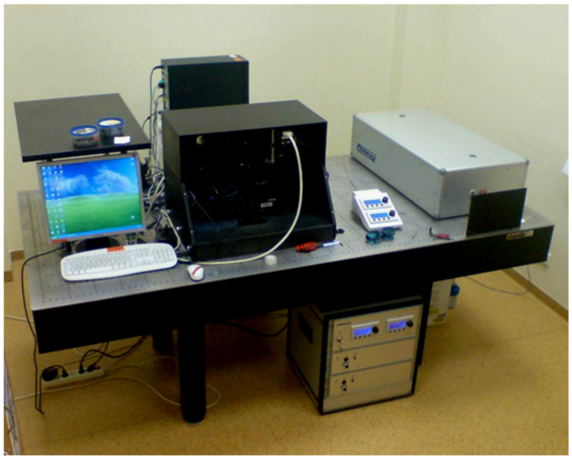
Several different micromachining strategies could be applied for precise cutting of steep-walled grooves on a steel surface. The two most common laser processing techniques are linear sample translation in respect to fixed focus position ("moving sample setup") and the scanning beam approach where laser beam is moved in respect to fixed sample position by means of galvanometric scanning and focused using an f-theta lens ("moving beam setup"). Each technique has its own advantages and disadvantages and should be chosen according to the application. A system of linear translation stages in combination with a high numerical aperture (NA) objective (sharp focusing) can be very precise in beam positioning, and the maximum traveling range (processing area) of such stages could be quite high. However, sample translation speed tends to be limited. The beam scanning approach does not have such drawback, but on other hand, it has limited processing area which is linked to the choice of focusing lens. With beam scanning large processing areas require low NA value lenses (soft focusing), and this can be an issue with power-limited laser sources in achieving radiation intensities required for efficient ablation. Both these techniques were tested for groove micromachining tasks.

Femtosecond laser technology utilized

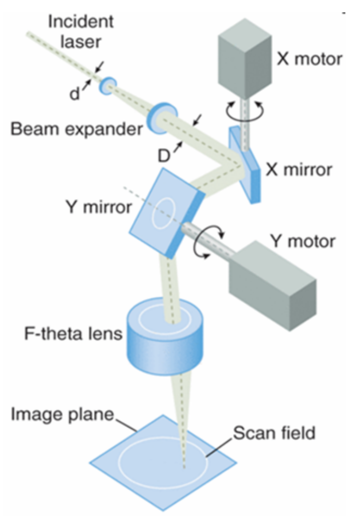
We have used femtosecond laser (PHAROS, Light Con-version, Ltd.), that was based on Yb:KGW, and had pulse duration 300 fs at 1030-nm wavelength, repetition rate up to 350 kHz and 6W average power (Fig.1). The optical-mechanical system used for machining grooves consisted of the laser, optical beam delivery components, a 3D linear stage positioning system (for "moving sample setup"), intellSCAN10 galvanometric scanners (from SCANLab GmbH) (for "moving beam setup"), computer and electronic control units. The method of "moving sample" while keeping laser's beam focus at fixed position was implemented with submicron position resolution. The positioning system consisted of three linear translation stages, which allow fast and accurate sample positioning. The accuracy of lateral stages was 0.3 µm, and the maximum travel speed was 30 cm/s. This gave plausibility to having a short processing time with a high-average-power laser.



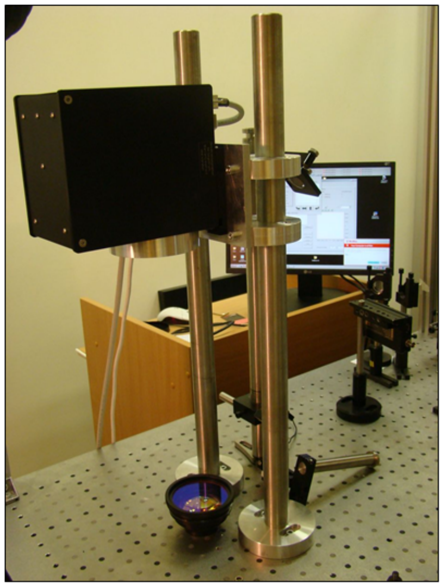
"Movable sample" system sketch



"Movable sample" system
(without beam delivery system)



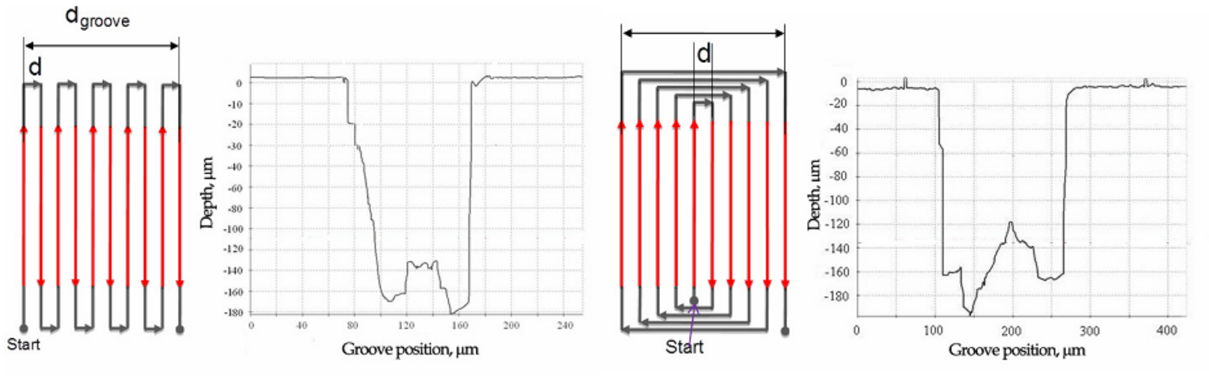
"Movable beam" system sketch



"Movable beam" system

Fig 1. Micromachining systems assembled at VULRC. In "movable sample" system the sample is moved with 3D linear stages with respect to laser beam position. In "movable beam" system the beam is moved with the help of two rotating mirrors across the sample.

In moving sample setup, the steel sample was attached to the linear translating stage, and laser beam was focused on the surface with focusing lens to spot diameter of 10 µm. Since this diameter was smaller than the required groove width, additional width was obtained with the implemented patterning algorithm. Various algorithms were tested as groove quality significantly depends on it. Two conventional scanning patterns: the raster algorithm and the spiral algorithm are shown in Fig. 2. With raster patterning, the required groove width was achieved by continuously translating sample up and down the groove and constantly shifting new line position by constant displacement *d*.



a) b) c) d)

Fig. 2. Raster patterning algorithm (a) and groove profile after patterning with hatch algorithm (b). The unsymmetrical slopes show the drawback of this algorithm. Spiral algorithm (c) and groove profile after spiral algorithm patterning (d). Slopes are symmetric and steep, debris are accumulated only at the bottom of the groove.

In such patterning grooves are always cut straight from one edge to the other. In the spiral patterning algorithm, the sample is translated in a spiral path with respect to the beam focus having pitch length *d*. In this configuration, groove cutting progresses from the groove center towards the walls.

The laser pulse energy was 20 μJ (2W at 100 kHz), and the energy fluence in the focus was as large as 30 J/cm^2. This value corresponds to strong ablation regime that leads to the efficient generation of ablation debris. The groove produced with raster patterning algorithm is unsymmetrical because majority of the ablated particles tend to stick to one side of the grove (Fig. 2b). This can be understood by comparing the ablation conditions at the first raster lines with respect to last: the last ablated line tend to pollute the previous ones, leading to asymmetric walls. To get deeper grooves, several repetitions of the patterning algorithm are necessary, and such debris accumulation becomes more evident. The spiral patterning shows much better results in terms of groove rectangularity and wall verticality (Fig. 2d). However, at the center of the bottom surface of the fabricated groove, a hill formed from adhered microparticles was observed. Those formations are particularly hard to remove; the accumulated particles remained even after cleaning the sample in the ultrasonic bath.

It was possible to reduce the debris sticking to the groove bottom by applying an inert gas (argon) jet to the ablating region. The gas jet tended to blow away debris from the groove improving the rectangularity. However, as seen from the Fig. 3, the jet presence reduced ablation efficiency by almost at half. The groove bottom surface becomes flatter, but shallower. This can be explained, by the fact that hot microparticles generated during ablation increase laser irradiation absorption and slow the ablation process. Laser polarization also strongly influences rectangularity of the fabricated groove. In order to reduce reflections from the wall it was essential to use laser polarization that is parallel to the groove. With polarization perpendicular to the wall, V-shaped grooves were formed (Fig. 3b). The experiments that determined the optimal displacement of adjacent scan lines (*d*) were also carried out. It was found out that at least 50 % of ablated regions should over-lap in order to get smooth-bottom structures.

The width of the groove is determined by the number of scanned lines in the algorithm, while the depth is scaled by repetitive scanning. As example, to fabricate a 280-μm wide and 170-μm deep groove, the required algorithm had 50 raster lines and 28 repetitions, using 20 μJ pulse energies at 100 kHz. Sample translation speed was 100 mm/s. Total cutting time for a 1-cm length groove was 15 minutes. The resulting groove is shown in Fig. 4 . No gas injection was used in this particular experiment. To form flat bottom we used spiral patterning algorithm, but the spiral direction was alternated each repetition (from groove center towards the walls and then from the walls towards the center). Such an algorithm gave bottom flatness equaling 10 µm (rms st.dev.). In comparison, the surface roughness of non-processed sample is 0.5 µm (rms st.dev.). No saturation effects (decrease of ablation rate due to wall absorption and defocus) were observed at depths up to 400 µm with these pulse energies and focusing conditions. It was found, however, that in order to get smooth grooves with steep slopes, groove width-to-depth ratio should be at least 1:2 or less. With deeper cavities, the bottom roughness became slightly worse, mainly due to debris that becomes hard to remove even after several washings in ultrasonic bath.

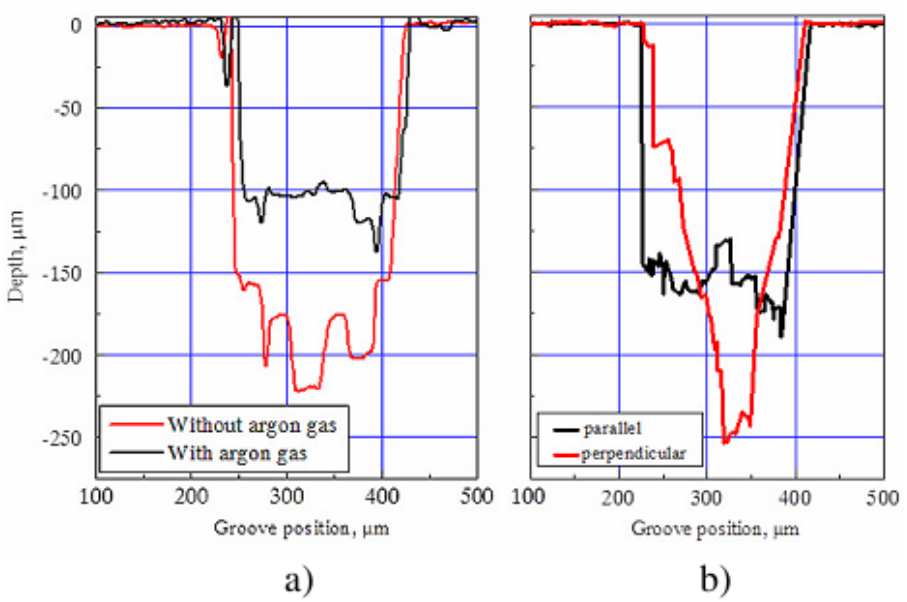


Fig. 3. Groove profiles made in steel a) with and without argon gas injection; b) with different polarization in respect to groove orientation. Processing parameters: 2W at 100 kHz. Sample translation speed in a) 40 mm/s; b) 30 mm/s. Spiral patterning algorithm with 10 repetitions.

Galvanometric scanner research

In order to micromachine with galvanometric scanner, an f-theta lens with rather long focus length needed to be used. Here we used lens that had 100-mm focal length. The focused spot diameter was approximately 40 µm. The larger spot size decreased laser fluency at focus and, respectively, ablation efficiency. We used 30-µJ laser pulses (6W at 200 kHz) in this experiment, which corresponds to 2 J/cm^2 energy fluency at the focus. Lower ablation efficiency requires greater number of patterning algorithm repetitions in order to achieve required depths. However galvanometric scanners do not have strict speed limitations, so processing speed could be much greater even taking in account higher repetition numbers. The scanning speed used here was 1000 mm/s. The typical groove cut in steel sample is shown in Fig. 4. We used spiral patterning algorithm that was repeated 145 times. Overall manufacturing time for 1-cm line groove was 120 s. Thus comparing with linear stages, the processing time is shorter almost by an order of magnitude. Manufactured grooves had steep walls; however, the bottom surface roughness was slightly worse and reached 20 µm (rms, st.dev.). Such roughness is sufficient for complete ceramic mesh installation into processed sample. More details on laser micromachining processes are presented in our publications [1-3].

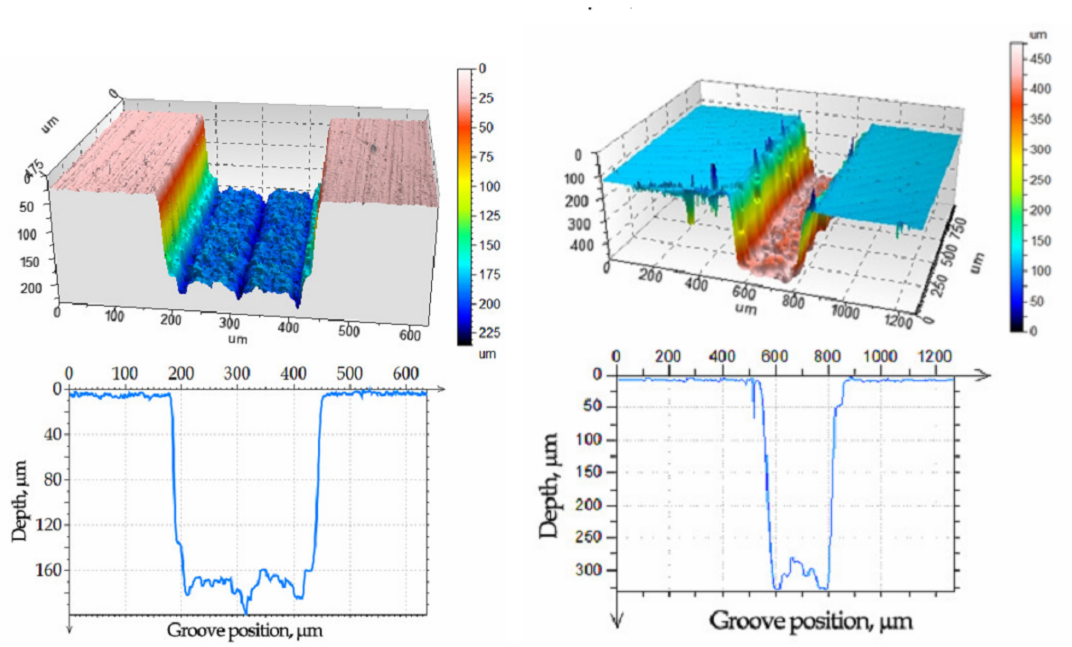


Fig. 4. Optimized flat-bottomed groove in steel made with spiral patterning algorithm (left). Typical groove profile cut in steel sample using galvanometric scanners (right).

Sensor prototype development

The range of samples treated in this project is shown in Fig. 5. They differed in size and geometry and manufactured grooves ranged from several millimeters up to 5 cm in length, with constant groove quality across the entire sample.

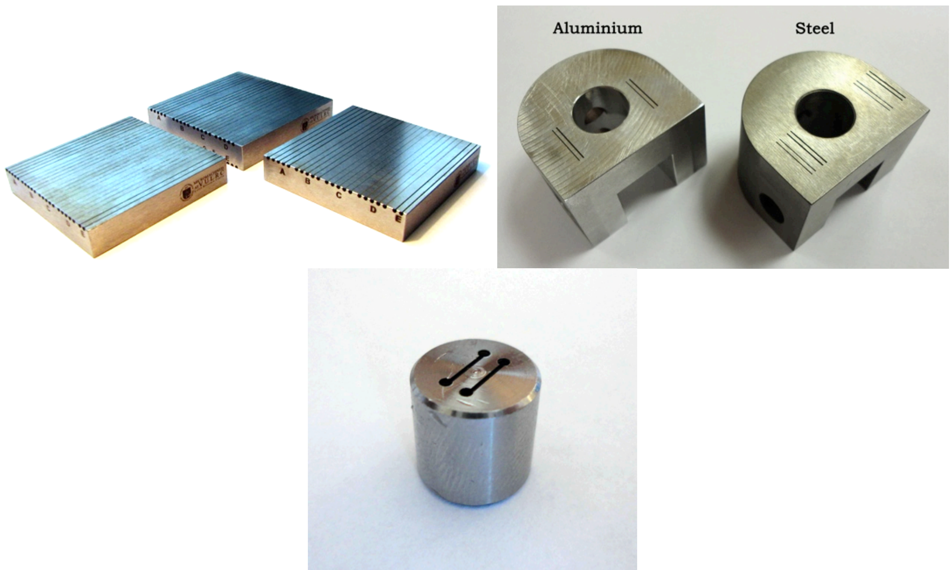


Fig. 5. Various geometry samples with fabricated grooves with width of 200 µm and depth of 300 µm or more.

State of the art and beyond: new innovative solutions

Developed laser micromachining system has wide adaptability and are not only suited for metal micro cutting. To solve the issue of contacting, holes and notches were fabricated in the ceramic fiber that was developed by other project teams and is the main constituent of mesh sensor. Such brittle fiber, which is not greater than 250 µm in diameter, has to be microcut otherwise it would not be possible to solder metallic contact wires to the mesh sensor. These microcuts are shown in Fig. 6. Both micromachining strategies were tested on fibers: holes were made with "movable sample" system, using circular patterning algorithm, while notches were done with "movable beam" system using spiral algorithm. The size and depth of the hole or notch are highly controllable and could range from several micrometers to macroscopic sizes by appropriate processing algorithm.

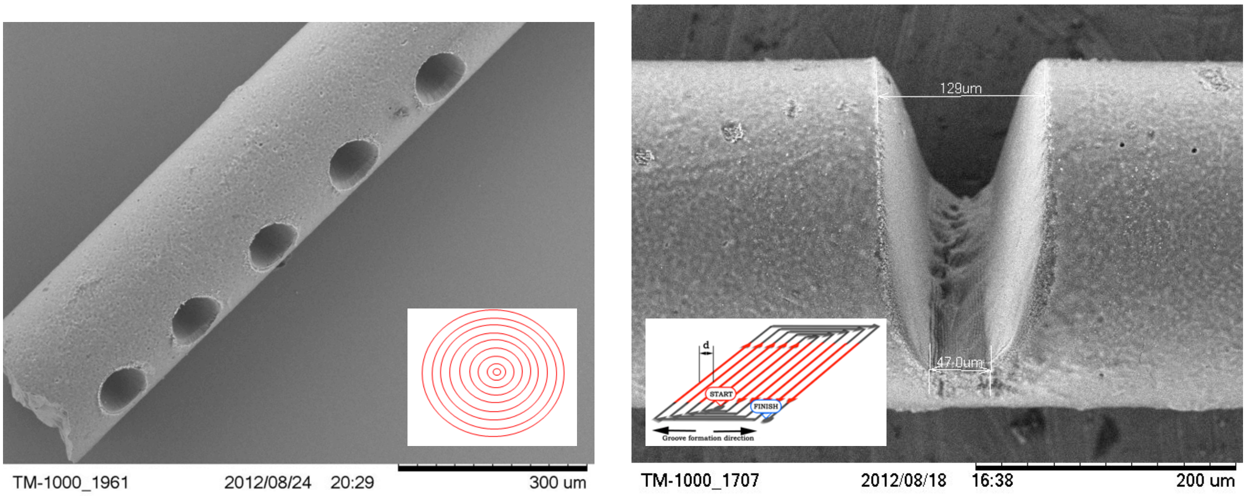


Fig. 6. Holes and notches made in the ceramic fiber with ultrashort laser pulses. The microcuting time of such structure is less than a second.

In conclusion we can state, that ultrafast laser micromachining technique proved itself remarkably in this project. All project micromachining objectives were successfully achieved. Also it is important to state, that there is still room for micromachining algorithm optimization, especially considering higher power ultrashort pulses. Lasers, capable to produce such pulses nowadays are entering the market. Such systems could even speed-up manufacturing process and groove quality even further.

1. **K. Kuršelis, D. Paipulas, T. Kudrius, O. Balachninaitė, V. Sirutkaitis**, „Experimental study on femtosecond laser micromachining of grooves in stainless steel", **Lithuanian J. Phys.** 50, 95-104, 2010.
2. **A. Urniežius, N. Šiaulys, V. Kudriašov, V. Sirutkaitis, A. Melninkaitis,** Application of time-resolved digital holographic microscopy in studies of early femtosecond laser ablation, Applied Physics A, Volume 108, Issue 2, pp.343-349.
3. **A. Baskevicius, A. Alesenkov, G. Chozevskis, J. Litvaityte, O. Balachninaite, D. Paipulas, A. Melninkaitis, V. Sirutkaitis**, Optimization of laser-ablation micromachining by choice of scanning algorithms and use of laser-induced-breakdown spectroscopy, *Proceedings of the 13th International Symposium on Laser Precision Microfabrication, June 12-15, 2012, The Catholic University of America, Washington, DC USA, Paper number #12-66, 1-6 p.*

2. Innovative ceramic development (Bath University)

In the first instance, the possible modes of operation for the ceramic steel mesh sensor were reviewed. The possibility of developing a transmission line sensor was rejected since although a sensor like this is technically feasible, the cost would be high and there are difficulties interpreting the data, since a fouling layer would cause big errors. Therefore the University of Bath, as part of WP3/Task 3E, proposed a sensing method based on a low frequency resistive measuring system.

A key aspect of the MesMesh concept is the ability to measure the level of wear occurring on the surface of the steel mould (substrate) without the need to dismantle the system for microscopic examination. The method proposed was to fill the grooves in the steel mould with an insulating ceramic material into which is inserted a conducting ceramic fibre (which is thus electrically isolated from the steel substrate). The conductive material should (a) wear at a rate comparable to the steel and (b) to have a resistivity which is large enough to realise an easily measurable change in resistance (approximately 100 Ω) when the surface is worn down by not more than 5 µm.

The general plan of the sensor concept is illustrated in **Fig 1.** The surface of the tool will be covered by a number of grooves running parallel as shown in **Fig. 1** and **Fig. 2** shows the end-view (i.e. the x-y plane is parallel to the page). Dimensions for the grooves are approximately 200 µm in depth (d) and also in width (w). The dimensions and composition of the conducting fibre will be in the order of 100µm. It has been calculated that in order to have a change in resistance in the order of 100 Ω for a 5µm wear, the ceramic materials would need to possess a resistivity in the range 10^2-10^4 µΩ.cm. For the purposes of this section a nominal value of resistivity of 5000 µΩ.cm has been assumed.

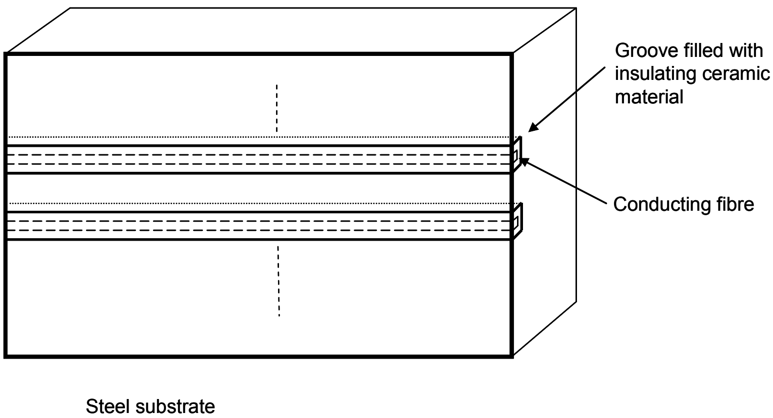


Figure 1: Outline of the instrumented tool viewed from above (x-z plane). The steel substrate includes a number of grooves which run in parallel in the x-direction. The grooves are filled with an insulating ceramic material into which is inserted a conducting fibre. As the fibre wears (z-direction) its resistance increases. The increase in resistance is detectable at connections spaced evenly along the length of the fibres (not shown) leading to a 3-D representation of the wear profile.

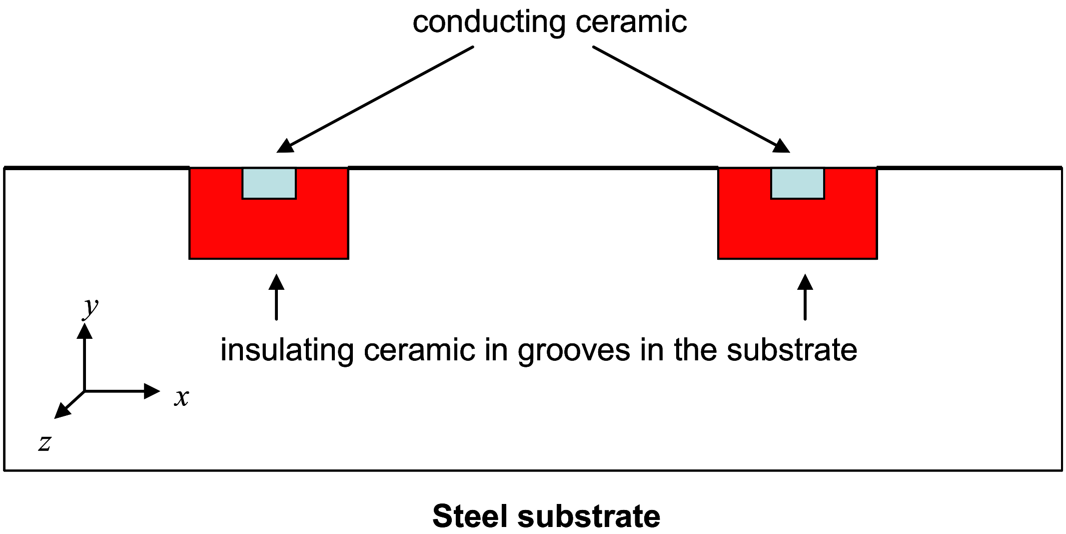


Figure 2: End-view (x-y plane) of tool showing the placement of the insulating and conducting ceramics in the groove of the steel.

As described above, the materials chosen for the mode of operation of the sensor require certain electrical, physical and mechanical characteristics. As part of WP3, the thermal expansion coefficient, the hardness and the wear rate of various candidate materials were characterised. The conductive ceramic Ti_nO_{2n-1} , chosen by University of Bath, met the challenge of matching these properties with that of steel. An insulating glass was also successfully chosen to offer insulation to the conductive ceramic and strong joint between the conductive ceramic and steel. In WP3, Task 3A and 3D the ac conductivity, permittivity and loss were measured from mHz to 1MHz and the microstructure of the materials was characterized. The electrical properties of the Ti_nO_{2n-1} were suitable for the mode of operation and they were related to the structure of the ceramics.

Finally, University of Bath was able to optimize the development process of the ceramics and developed conductive ceramic fibres of tailored and reproducible resistivity. The resistivity that was preferred for the application was 0.03Ω.cm. The TiO_2 fibres in the 'green' condition are produced in EMPA Research Institute in Zurich by Dr. Frank Clemens. The TiO_2 powder (99.5%, 0.3 μm) is added to a mixture of polyethylene binder and surfactant and the feedstock was produced with a torque rheometer. The fibres are extruded with a die of 300 μm (Fig.3).

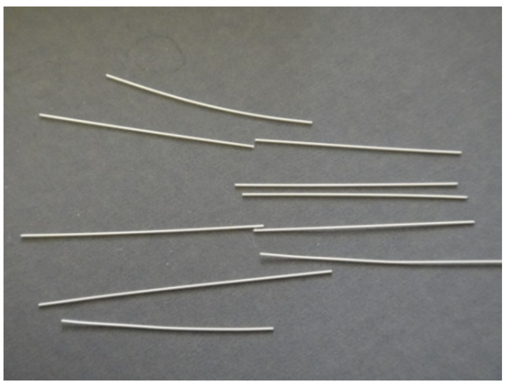


Figure 3
Green TiO_2 fibres (Ø=300 μm, l= 3-8 cm)

The green fibres are sintered following the sintering regime presented in Fig. 4 at 1300°C with a step at 500°C in order to burn out the binder. This sintering profile is selected to control the grain growth.

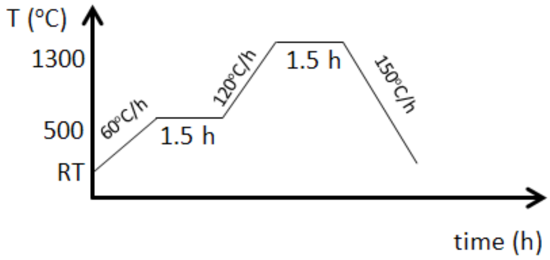


Figure 4
Sintering patterns for the green titania fibres

In order to obtain the Magneli phases fibres the TiO_2 sintered fibres are reduced through a carbon-thermal process performed in a tubular furnace at 1300°C for 1 hour (Fig. 5).

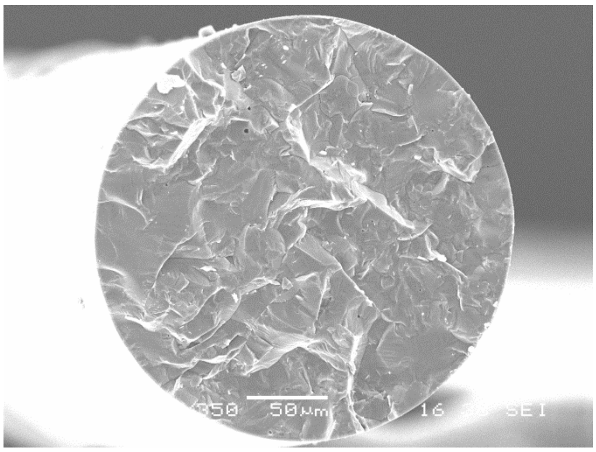


Figure 5: SEM image of Magenli phases fibres reduced at 1300°C for 1 hour.

3. It is all about bonding (MET)

At the early stage of the project UAB Modernios E-Technologijos (MET) has performed a scientific study of material and design of the bonding technology and proposed the methodology of the further materials and bonding technology investigations. Primarily it was expected that the sensor embedded into the mould must work in the high frequency (possibly in microwave band). The sensor itself is a kind of conductive ceramics placed in the groove that is ablated with laser in the steel housing.

As measurements at a very high frequency range are technically and methodologically complicated it was performed a theoretical research on several cases of high frequencies with different measured parameters and frequency values, and in case of direct current (DC) regime, when resistances of first and second sensors or difference between them are measured in DC regime. In case of direct current regime the ceramic was isolated from steel housing by coating inner surface of laser ablated groove with non-conducting thin film. It was proved that this additional technological task is not complicated comparing with difficulties expecting in the case of high frequency.

Bonding of sensor and measuring equipment highly depends on range of measurement frequency. In case of direct current regime can be used any kind of wire (one end is connected to ceramic and another – to equipment); length and diameter can be selected by convenience and reliability. In case of very high frequency bonding becomes rather complicated, because measured parameter often is a summary function of geometries of wire and sensor.

Equally important objective was the selection of the suitable high frequency transducers ensuring the waveguide effect of the composite. MET has proposed a possible realization of sensor (see Fig. MET-1) in which the initial groove has been filled with insulating ceramic and sintered. New grooves had been micro machined in the ceramic and filled with conductive material forming a line suitable for microwave measurement.

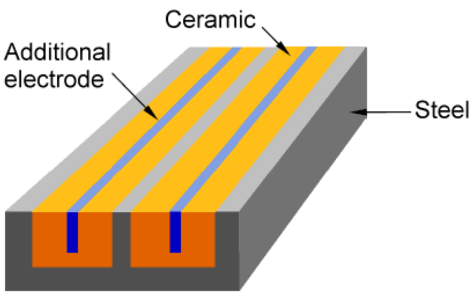


Fig. MET-1. Schematic view of the sensor with additional conductive electrode added by laser micromachining of the ceramic.

The theoretical model has been considered and the method of solving Laplace equation described. Used method has been proved through calculation of parameters of the microstrip line and comparison with analytical solution. As a result of investigation of properties of the groove type line depending on its dimensions two types of the sensors were proposed and calculations of microwave wave propagating in a groove type transmission line considered. The phase of reflected wave from dielectric ceramic has been measured in a frequency range 100 MHz – 12 GHz.

A resonance phenomenon has been found at higher frequency in a tablet shaped samples providing anomalous shift of the phase of the reflected wave. Experimentally measured phase shift at resonance conditions reached roughly 0.7º per mm thickness of the tablet while far from the resonance phase shift is smaller by one order of magnitude. Resonance shifts to lower frequency by increasing relative dielectric constant of the sample, its radius or thickness. It is very desirable to find similar resonance at a lower frequency

An experimental investigation of two microwave measurement techniques has been performed. Were tested two types of samples: dielectric sample without metallic shade covering it (see Fig. MET-2) and dielectric sample covered with metal shade (see Fig. MET-3). In both cases was used a coaxial line filed with

Teflon (ε = 2). Were calculated dependencies of the reflection coefficient and the phase of reflected wave on frequency for two different thicknesses of dielectric sample.

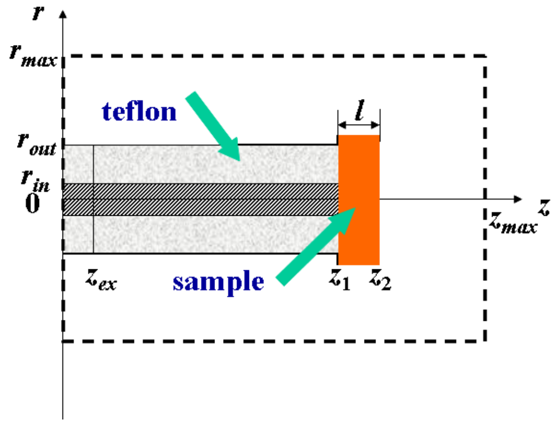


Fig. MET-2. A view of a section of the coaxial line and sample without metallic shade covering it. Coaxial line filed with Teflon (ε = 2) is proceeded by a dielectric sample. Radius of the inner metal conductor r_{in} = 1.5 mm, outer – r_{out} = 4.9 mm, characteristic impedance of the coaxial line is 50 Ω. Sample fully covers the dielectric of the coaxial line.

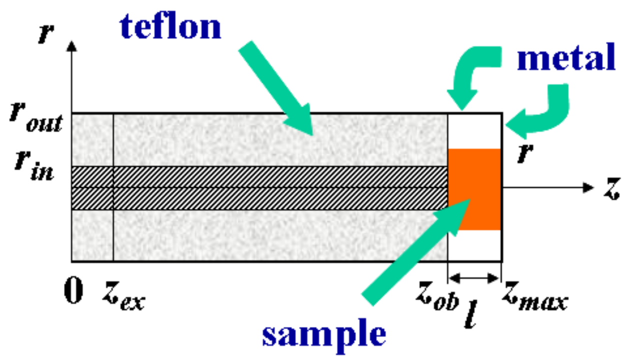


Fig. MET-3. A view of the section of coaxial line with a sample.. Coaxial line filed with Teflon (ε = 2) is proceeded by a dielectric sample covered with a metal shade. Radius of the inner metal conductor r_{in} = 1.5 mm, outer – r_{out} = 4.9 mm, characteristic impedance of coaxial line is 50 Ω. Sample radius denoted as *r* its length – *l*.

Coaxial line loaded with dielectric sample without metallic shade has been investigated numerically using FDTD (finite-difference time-domain) method. The results obtained for this case are very suitable for practical applications.

Investigations have demonstrated that measurements at very high frequency range (HF) are realistic in principle. However, they are complicated and expensive. Therefore the decision to shift from HF to DC has been made and the further work plan, scheduling and concrete implementation actions have been adjusted to reflect the above-mentioned decision.

One of the most important tasks carried out by the MET was selection of a suitable low resistance bonding material and the reliable transducer bonding to the ceramic surface technology development. A number of different contact types on conductive ceramic have been investigated. It has been shown that the quality of contacts improves when they are processed at higher temperature. The best ohmic contact characteristic demonstrates Pt contact providing sufficiently good linearity in a range of ±1 V of applied voltage. Such voltage is sufficient to perform DC measurements of sensor resistance.

DC measurements have been performed on the ceramic samples provided by Bath University. From all tested metals suitable low resistance bonding material to conductive ceramic the best results demonstrate Pt and Al contacts. They exhibit linear current-voltage characteristic and the lowest values of the measured average specific resistance therefore can be used for dielectric ceramic connection as a sensor into measurement circuit. It is obvious that DC measurement technology is simple and cheap method to measure sensors wear in the mould.

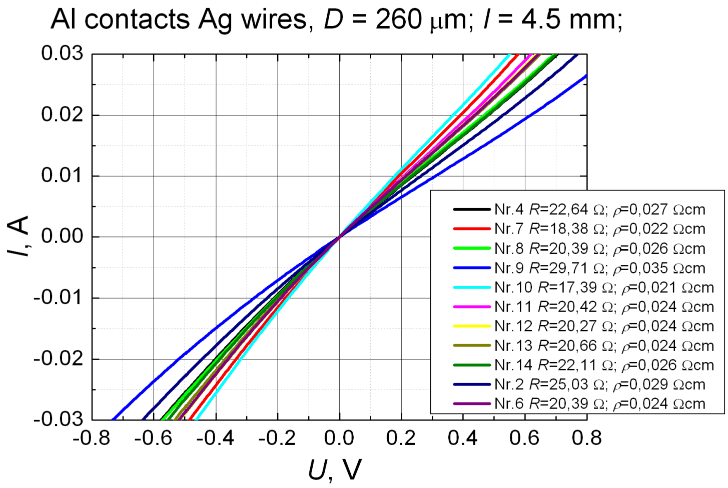


Fig. MET-4. Measured current-voltage characteristics of fiber samples with Ag wires fixed in holes. Contacts were formed and wires were fixed using liquid Al paste. Dimensions of the samples, their resistance and resistivity are shown in the figure.

During the second half of the project the main attention has been paid to the contact processing on the fibres and to the investigation of their characteristics. A liquid Al and Pt paste has been used for contact manufacturing. Contact quality was tested by measuring current-voltage characteristic of the sample made from the fibre with wires attached to the contacts (see Fig. MET-4). The layout of contacts with holes drilled in the fibre using laser micromachining technique (performed by VULRC) and wires fixed in those holes using liquid Al paste was considered (see Fig. MET-5).

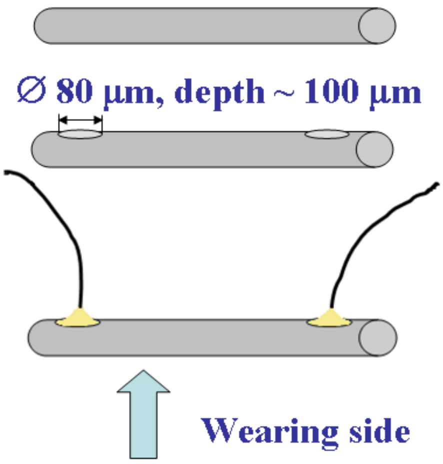


Fig. MET-5. Proposed layout of the sensing element with holes. From top to down: the fibre sample; the fibre sample with holes, the fibre sample with attached wires.

In conclusion it should be stated that:

- Al contacts show the best results for bulk samples and fibres demonstrating low contact resistance and perfect linearity of current-voltage characteristics.
- Specific resistance of the fibres with Al contacts in the range of 0.025 – 0.05 Ωcm has been measured.
- Applying of higher than 30 mA current to the conductive fibre with Al contacts leads to the irreversible change of their current-voltage characteristic.
- The issue with attachment of wires to the contacts surviving at higher temperature has been solved using liquid Al paste for producing contact and wires fixing.
- The issue of overheating of fibres, when drilling holes in it, has been solved by VULRC using less powerful laser pulse and more sophisticated hole drilling technique.
- Measured specific resistances of the fibres with Al based contacts and Ag wires fixed in drilled holes were in the range 0.021 – 0.035 Ωcm that coincide well with the results of measurements on unprocessed fibres presented earlier and lets to conclude that improved mechanical processing does not influence electrical conductivity of the fibres.

4. Electronic's to tie it all together (Pera)

The MesMesh concept is to be able to measure wear on the surface of steel mould tool in real time. We aim to do this by measuring the electrical characteristics of a conductive ceramic material which will be embedded into a groove on the surface of the mould tool. As the surface of mould tool wears down, the ceramic material will also wear down at the same rate. This in turn will increase the resistance of the ceramic material for which we will develop electronic hardware to measure.

From the mid-term report, a DC resistive measurement was chosen to be developed to detect the wear of the ceramic microstrip. The proposed electronic hardware must be capable of:

- Monitoring the wear of the mould tool by measuring the resistance of the ceramic insert
- Use a microcontroller along with a pair of multiplexers to monitor up to 8 ceramic microstrips on a tool
- To provide a visual aid for the operator to easily determine the condition of the tool
- To provide historical data in order to predict the wear of the tool

A block diagram of the system can be seen in figure Pera-1.

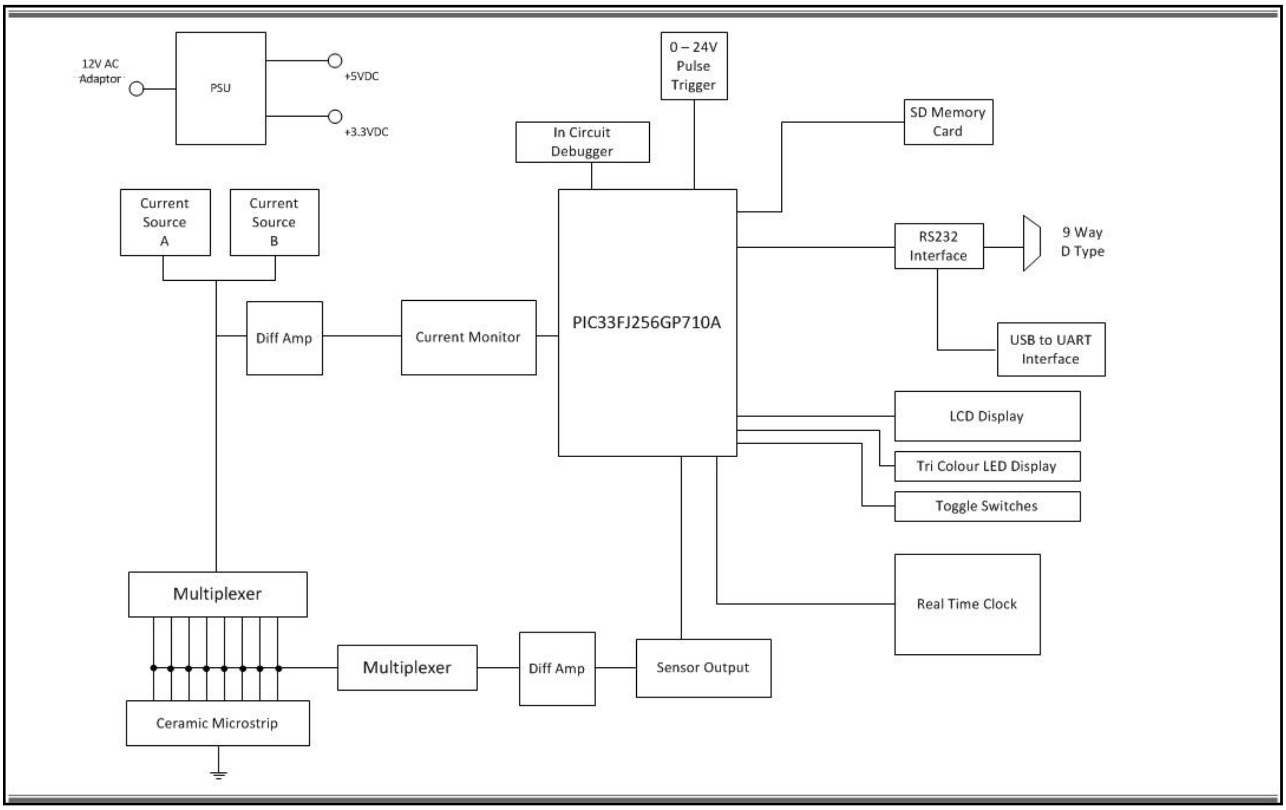


Figure Pera-1 - Block Diagram of the MesMesh System

PCB layout

The electronic schematics are then converted into a PCB layout which can be manufactured and populated. An image of the final assembled PCB is shown in figure Pera-2.

Figure Pera-2 - Assembled PCB board

The microcontroller has been programmed using a Micro Chip MPLAB ICD (In Circuit Debugger). The programming of the microcontroller consists of:

- Configuring the input / output pins on the microcontroller
- Monitoring the constant current by measuring the voltage across a known resistor
- Monitoring a calibration resistor
- Reading the resistance of each ceramic sample by measuring the voltage across each resistor
- Setting the 2 multiplexers to select each sample at the correct time and speed and to perform the reading
- Configuring the analogue to digital signal
- Configuring the RS232 communication protocol to interface with the GUI
- Interfacing with the LCD panel and LED status indicators

Further detailed information on the operation of the MesMesh board can be obtained in Deliverable 8 - Mock-up Versions of the Signal Transmission and Receiver Electronics.

Graphical User Interface

The electronic hardware is connected to a computer via the RS232 connection to display the status of up to 8 ceramic microstrip sensors on a given mould tool. Figure Pera-3 shows the graphical user interface (GUI) that has been developed. The interface has been developed trying to keep operation simple and allow users to quickly learn and familiarise with the different features and operation of the software.

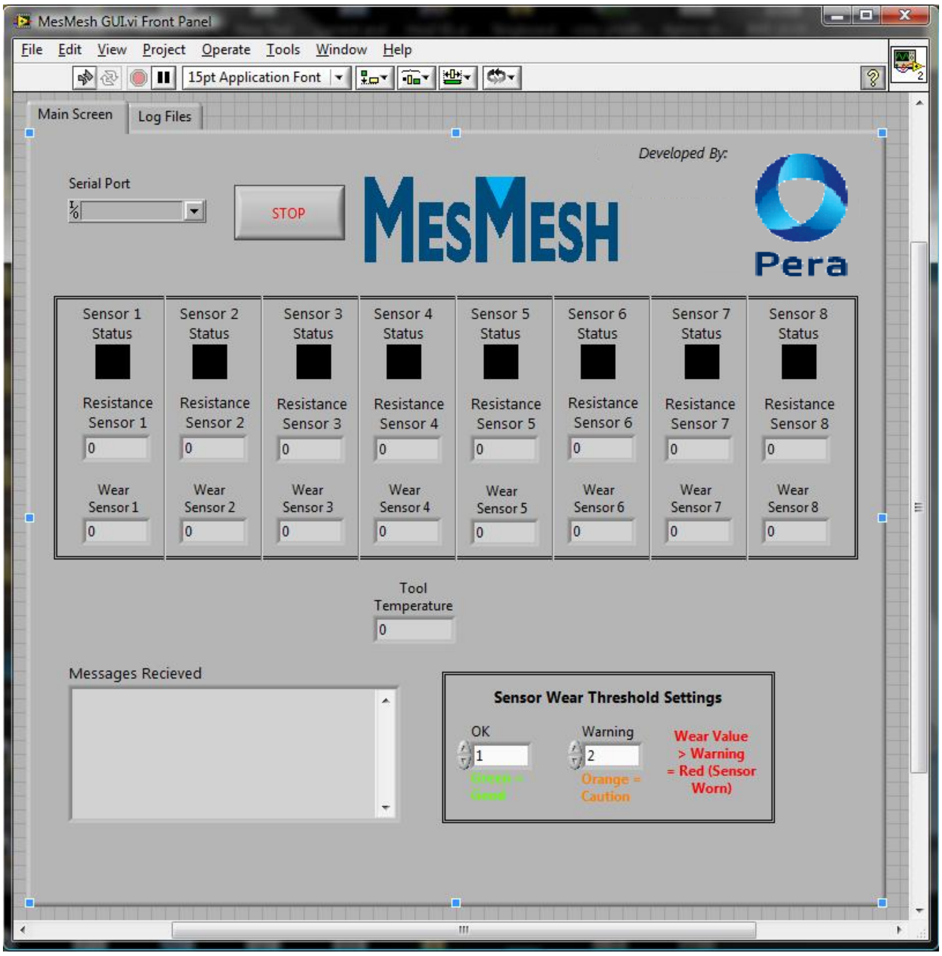


Figure Pera-3 - Graphical User Interface (GUI)

5. Integration and testing/validation (Multiple partners)

The manufactured sensor held in a mould tool is shown in figure Pera-1.

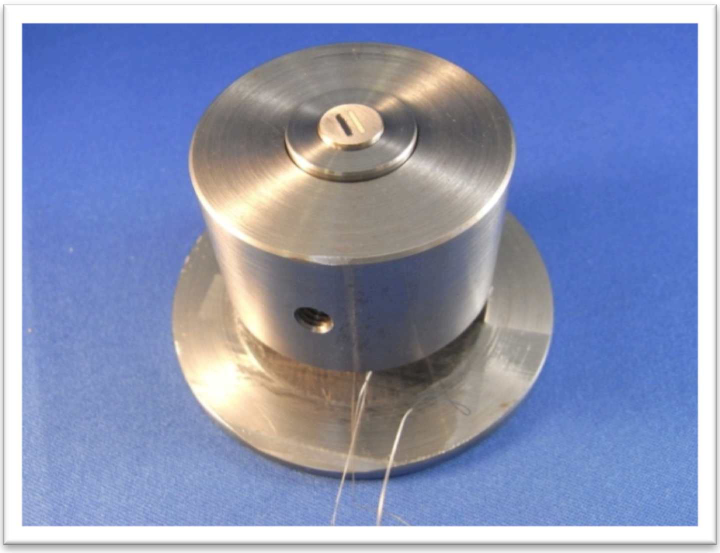


Fig. Pera-1 – Ceramic sensor in mould tool

The mould tool is required to mould the sensor firmly in position whilst undergoing a grinding process. With the grinding machine we are able to simulate wear of the ceramic microstrip rapidly. Using the grinding machine, 10μm is removed from the surface of the sample and measurements are taken with a CMM (Co-ordinate Measuring Machine) to record the actual amount removed.

The resistance of the ceramic microstrip is then measured with the MesMesh system and with an LCR meter. Both devices are used to verify the results of the developed MesMesh system during the testing stage. Figure Pera-2 shows a process flow diagram for the testing procedure used to verify the MesMesh system. By grinding the ceramic microstrip repeatedly in 10μm and recording the resistance we are able to build up a relationship between wear and resistance. We should notice that as the microstrip wears down, the resistance increases.

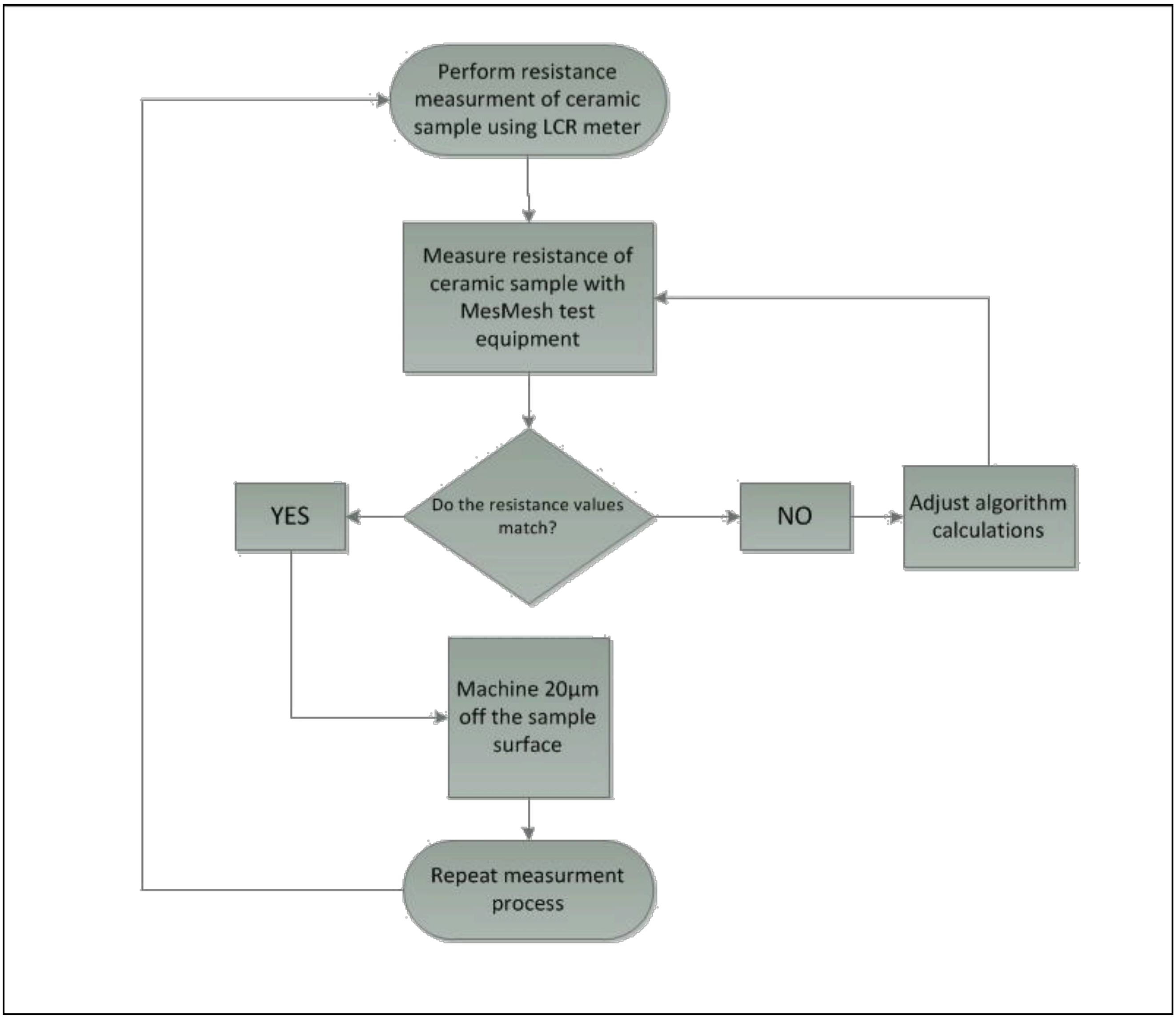
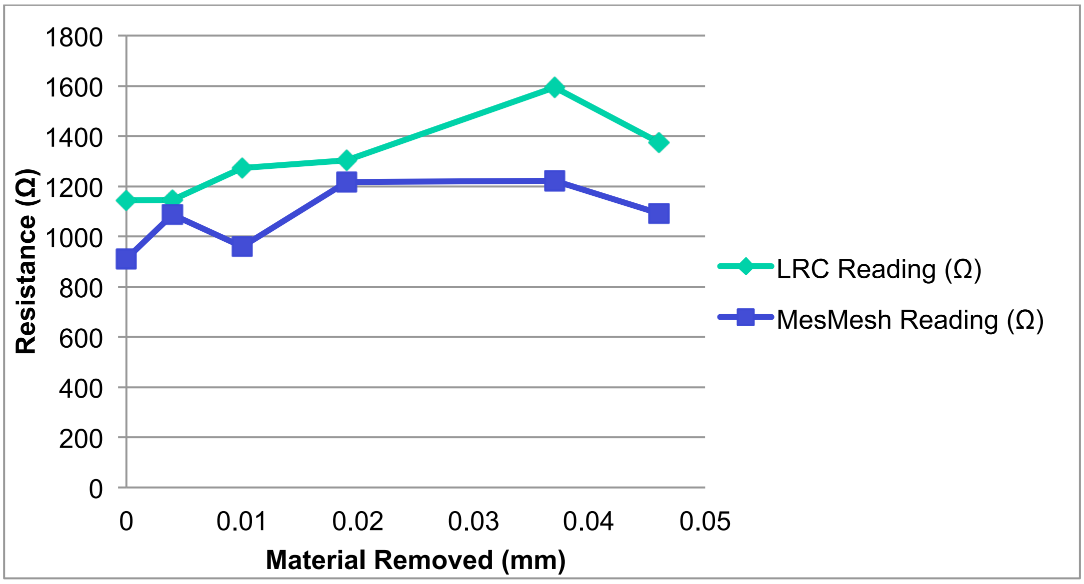


Fig. Pera-2 - flow diagram for the testing procedure

1. Pera and Müggler: Test Data 1

Graph Pera-1 shows the results from sample 1. As the microstrip is worn down, the resistance of the microstrip shows a gradual increase. However, there appears to be no correlation between the MesMesh system and the LCR meter. On this sample no signal was recorded on the control microstrip which is below the surface. This could be caused by the wire bonding or the extension cable becoming damaged. Without any data from the control ceramic, it is not possible to tell if there is a problem with the MesMesh hardware or with the ceramic itself. By having both pieces of data we would be able to eliminate one of the errors. Further testing on new samples is required in order to verify the MesMesh hardware.



Graph Pera-1 – Test sample 1 of Wear against Resistance from Pera

Following several trials which showed a similar trend it became apparent that that an error was occurring caused by a short circuit between the bonded wire and the body of the ceramic housing. In order to overcome this issue, the bonded wire would need to be fully insulated by placing the wires through a ceramic tube thus ensuring no contact can be made with the steel body (figure Pera-3)

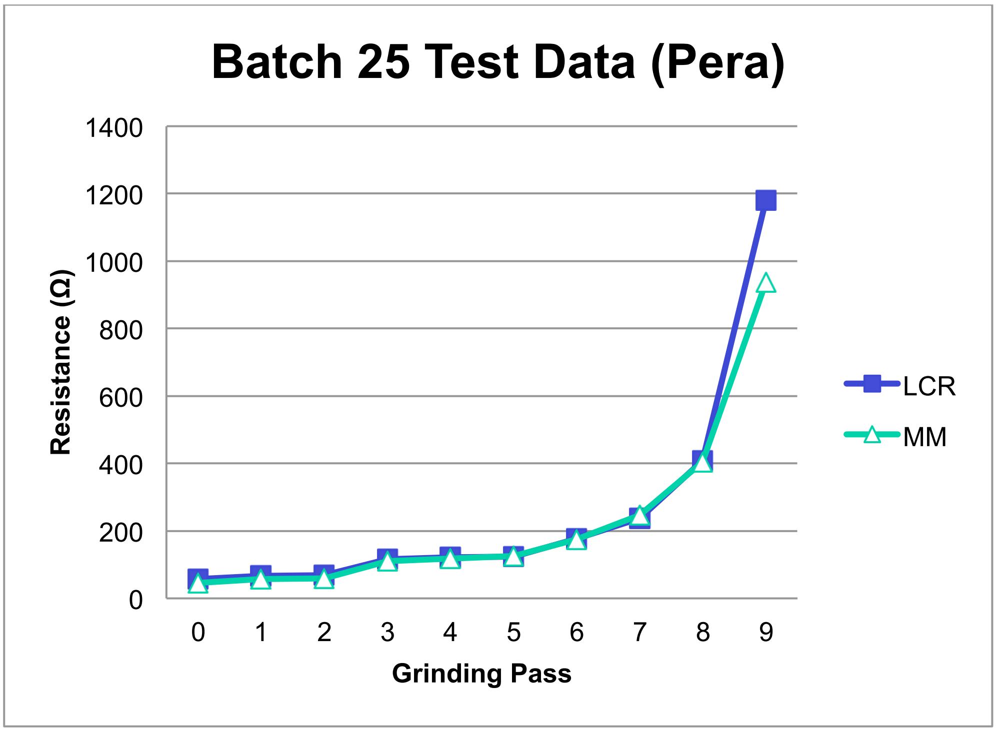
Fig. Pera-3 – Sensor with ceramic tube insulating the wires

Following the successful process of insulating the wires, further trials were carried out to test and validate the MesMesh system.

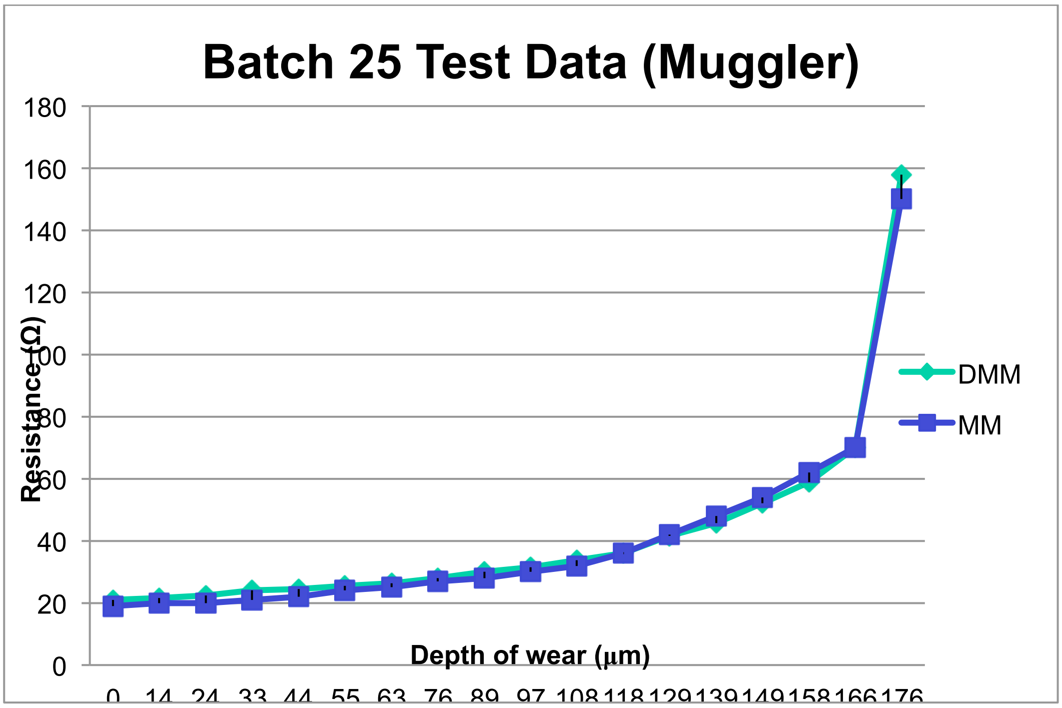
Pera and Müggler: General results of testing

Batch 25 was sent to both Pera and Müggler for testing. This was to allow the end user to test the MesMesh equipment and to verify that the data capture is working correctly.

With a suitably prepared sample, accelerated wear trails where carried out and resistance measured using both the MesMesh monitoring system and the LCR meter. Graph Pera-2 below shows the results obtained from the trials carried out at Pera. Graph Muggler-3 shows the results obtained from trials carried out by Muggler.



Graph Pera-2 - Test data carried out by Pera



Graph Muggler-3- Test data carried out by Muggler

The test data from batch 25 carried out by Pera and Muggler both show a similar trend. Unlike tests carried out before, there is no sharp rise and fall in resistance. This indicates that it is esential to cover the holes completely to stop any swarf entering the hole.

Whilst the trend of the 2 graphs are similar, there resistance values are different and the resistance at the point of failure is also different. These difference are due to inconsistancies with the ceramic microstrip sensor. Ideally, in order for the ceramic microstrip to have the same resistance vaules they need to manufactured with identical dimensions. Until the manufacturing proces of the ceramic microstrip sensor has been optimised the resistance value will differ from sample to sample.

Matrican and Balpol: Test 2

Two types of testing and validation were performed by Matrican and Balpol. Firstly, Matrican did environmental testing on location at Matrican. Secondly, Balpol performed tests on location in two types of moulding machines.

i. Environmental testing by Matrican

The sensors had been submitted to tests of contact with different raw materials. Here we tested 3 sensors, exposed to 7 different materials during the time of 4 months, with the purpose to analyse how the sensors would be react to the materials under different environmental conditions.

The tests of the sensor were performed with injected materials: PA, PA66, PA6 30% glass fibre, PA66 50% glass fibre, PP, PE and MIM (metal injection moulding). Some of the materials are shown in Fig. Matrican-1 below.

Fig. Matrican-1 Samples of the different materials

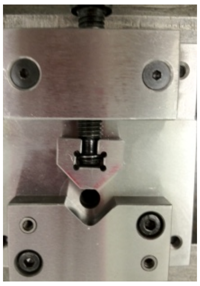
The sensor was tested for 4 months, where the sensors was exposed to different raw materials. Each test showed that no changes had been appreciated in the nominal value of the measurements, linking the sensor with the raw material and the environment. It therefore holds up well under different circumstances.

For further details on the environmental testing see 37month Technical report.

Mould machine testing

The testing and verification process included several steps.

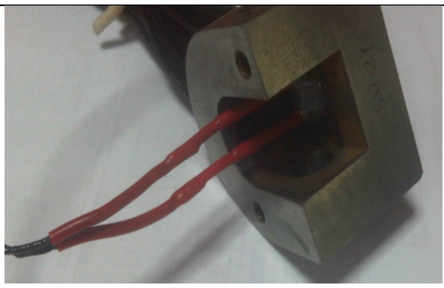
- The sensor was inserted in the “tool to hold the sensor” to verify the initial data with the verification program on the three-dimensional machine. (see fig. 1)
- The control points were determined
- Automatic verification of the control points
- Preparation of the data base for recording the readings
- Measurement data output generated.
- Introduction of the piece/sensor into the mould tool, prototype plate (see plate fig. 3).

		
Fig. 1	Fig. 2	Fig. 3

Pera supplied the MesMesh hardware and software along with an installation document for each end user. Balpol and Muggler have both successfully installed the software onto a laptop computer and have carried out trials with the MesMesh equipment and sensor on a selected mould.

As agreed Balpol tested the MesMesh system on two different types of the mould – EPS/alloy mould (expandable polystyrene) and PP/steel mould (polypropylene). All tests were made to utilize as much time as possible, because of equipment running on very tired schedule and to install MesMesh system we need to stop the machine for a couple days.

a. The EPS testing

Unfortunately we were not able to get readings with fully integrating the MesMesh equipment. We managed to put the sensor in to the mould, but in process of mould installation to the moulding machine, wires were clamped between cooling pipes and back support parts and they were pulled out from the sensor. It's too many black spots and sharp corners. From the tests performed without the wires we have found that the alloy is wearing quicker than the ceramics. This indicates that further research is needed on the preselected ceramics for the alloy mould.

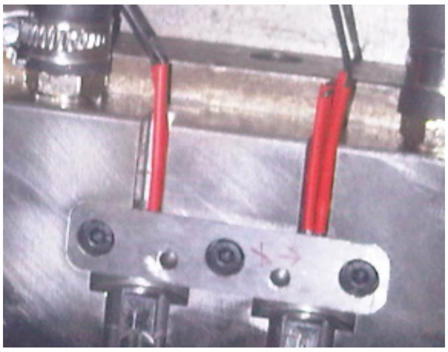
After not getting readings we dismantled the set-up and we realize what had occurred. It seems that empty cavities made to help easy installation was not functioning as intended. We therefore suggest that when utilizing EPS moulds the critical part is not a position of the sensor, but getting the wires out of the mould in the process of installation. The actual clamping (closing) of the mould is going on that time which creates some difficulties.

Summary results on EPS testing:

- From outside sensor is not damaged after over 100.000 cycles
- In EPS moulds it is very important to plan wires exit
- Big possibility to damage sensor during cleaning of the mould
- Sensor can handle fats and radical changes of heat up to 140 Celsius
- The sensor should be planned in design stage, so special channel and exit can be built for wires
- Ceramic is perhaps not the best material for sensors on alloy mould's.
- A mould with already integrated system would be preferable

The PP/steel test

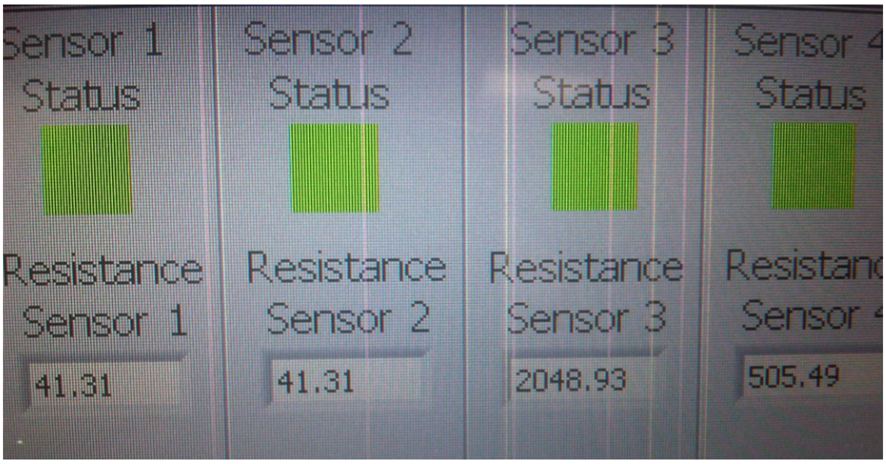
When testing the sensor in the PP moulds, Matrican built the portable part of the mould with sensors included. For the final test's we got portable part with four sensors:



After visual inspection we found that one of the sensors was already broken from outside surface. We marked it as sensor number 3. Number 1; 2; 4 were still ok.

It took several hours to set up and then to place mould in the machine. During this process, the wires were in the way, heavy metal, huge spanners and fragile sensors created a difficult environment.

Despite this, we succeeded to get a reading:



As you can see sensor number 3 was non-working from the beginning. After couple of hours sensor number 4 was broken as well. The reason being that the manual ejection of parts is under extreme influence. Later by monitoring sensor number 1 and 2 we realized that resistant is changing even during one cycle. Changes are not big, but I think it means that pressure, heat, connection with PP has effect on readings.

Summary results for the PP machine testing:

- Critical thing is position of the sensors
- Critical thing is the way how sensors are integrated into the mould
- The testing of monitoring sensor during use has been performed in real working environments.
- Potential of the system is extremely promising in a broad variety of applications
- Some optimization is needed on location.

Conclusion

We have demonstrated successfully that the MesMesh system can accurately measure the resistance of the ceramic microstrip. This has been verified by comparing the MesMesh resistance reading with a LCR meter. We have overcome issues relating to short circuiting of wires and unwanted noise through swarf inside hole by insulating the wires and filling the holes with resin. Furthermore, a solution to extending the wires to be more robust has been found at the point of manufacture.

The MesMesh system along with sensors has been sent to project partners for integration into their equipment. We have received positive results from one of the project partners which assist in verifying test data results.

During on site testing, some issues still need optimization. Despite that, readings were made during testing of the sensor in a working mould machine.

We are now able to make samples which can give resistance readings as expected in that the resistance of the ceramic increases as it wears down. In order to be able to predict wear rate from resistance we need consistent samples in order to be able to measure the resistance repeatedly.

1.4 The potential impact

Economic and Industrial impact

Plastics manufacturing in Europe is still subject to sustained pressure for improved standards of moulded parts quality, reduced product development time and lower average variable cost (cost per unit of output). The aim of this project has been to provide a viable solution to the manufacturers concerning improved standards, quality and reduced development time and costs areas.

In regard to price, the technology developed in the MesMesh project will allow the companies to cut their production costs by reducing significantly the level of output of scrap parts, thus optimizing the manufacturing process and providing them with opportunities for exploitation of economies of scale.

A fundamental strategic aspect of the proposed solution is that it facilitates the manufacturers of plastic parts to increase the quality of their output. The constantly increasing requirements imposed on moulders often exceed their capabilities as evidenced by long product development cycles, excessive tooling costs, low process yields, and inferior product quality. Failure to comply with the quality requirements set by the OEMs can result in severe penalties on moulders, and even can lead to complete loss of business. Moulders rely heavily on visual inspection and other sampling and quality assurance techniques, which do not necessarily guarantee moulded product quality. The plastics industry requires improved quality control technology that provides assurance in an automated fashion, without a constant feedback from a human operator. The sensor prototype has a great potential in addressing this need by providing an advanced solution that will guarantee more efficient quality control and minimum level of scrap parts.

To maintain a cost advantage, the plastics manufacturers must reduce the mould changeover time. Hence there is a constant need in the injection moulding sector to reduce machine downtime and to maintain production continuity. Even with quick mould changes the production start-up can be a prolonged process due to lack of set-up and control of proper moulding conditions. As such, the industry needs more consistent optimization procedures which guarantees moulded part quality in reduced set-up times. The technology accruing from the MesMesh project addresses directly this need by offering the possibility of preventive maintenance.

Once the technology is matured, it will be possible to migrate the technology into other markets. Seeing that injection moulding is a very big market on its own, and plenty of spill over markets are readily available, we have identified this as a good market to mature the technology and promote and disseminate the technology.

Environmental Impact

The sustainability of the technology and the environmental benefits of the MesMesh sensor prototype revolve around the significant reduction in the output level of defective parts. The minimised level of plastics waste production is the key to the environmental benefits, resulting in lower level of pollution, as well as in considerable energy savings. According to a 2001 Environment Agency report[1], 80% of post-

[1] http://www.wasteonline.org.uk/resources/InformationSheets/Plastics.htm

consumer plastic waste is sent to landfill, 8% is incinerated and only 7% is recycled. Hence, reducing the amount of plastics waste requiring disposal can have several other advantages:

- Conservation of non-renewable fossil fuels – Europe's plastics production uses 2% of the world's oil production, 1% as feedstock and 1% during manufacture;
- Reduced consumption of energy;
- Reduced amounts of solid waste going to landfill;
- Reduced emissions of carbon-dioxide (CO_2), nitrogen-oxide (NO) and sulphur-dioxide (SO_2).

Consideration of Gender Aspects

In accordance Articles 2 & 3 of the Treaty of Amsterdam (1997) and other EU policy directives (COM (96) 67 final) and reports (EUR 2002) the MesMesh consortium committed to incorporating the principles of gender mainstreaming throughout the various elements of the project[2,3]. The consortium made every effort to ensure that the work plan and related activities contributed to the promotion of gender equality wherever possible, and none of the activities within the project contributed to gender inequality or aggravated existing gender inequality. The following objectives underpinned our approach to gender issues:

- The consortium sought to ensure that women and men had equal opportunities to participate in the various parts of the project.
- In addressing diversity, the consortium took account of the different situations needs and interests of women and men.
- The project sought to contribute to reducing inequalities between women and men. Female researchers and administrative staff were employed when possible.
- The consortium sought to employ female participants to positions that are visible and influential e.g. one of the main performing researcher at Bath was female and the project manager of the whole project was female.
- During the project all the participants were visible through the dissemination material, and in this way the female participants can act as role models for young women about to select their career path.
- The consortium also promoted a policy where time off or flexibility for family commitments is allowed and respected and during the project monitor and control equal opportunities within the team and the project management process to ensure constant vigilance of the gender sensitive issues.
- No gender sensitive issues arose during the project.

Ethics
The project did not involve research on animals, humans, human embryos, privacy or personal information, developing countries or dual use.

[28]Communication from the Commission (1996) Incorporating equal opportunities for women and men into all community policies and activities. COM (96) 67 final.
[3] European Commission 2001 Gender in Research: Gender Impact Assessment of the specific programmes of the Fifth Framework Programmes.

1.4.1 **Project public website and contact details.**

Website: www.mesmesh.eu

Contact information of project partners

Partner legal name	Contact Person	Email
PERA Innovation	Paul Holdsworth	Paul.Holdsworth@pera.com
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