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System and process development for functionalization of electrical components by laser-based gold micro deposition

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Abstract

During the manufacture of electrical contact components, the contacts are coated with precious metals. Currently, energy- and resource-intensive electroplated coatings are used. A sustainable alternative is the local functionalization of sheet parts using small gold spots with the appropriate system technology for laser-based micro wire deposition. However, the necessary process reliability and required short cycle times represent a challenge for the technology. Within this paper, the system development of a stand-alone coating system is described. The approach presented is based on a laser beam deflection unit, fully automatic laser system control, a 5-axis wire head and a quality assurance system. An analysis of the deposition results was carried out, taking into account crucial process parameters. The resource efficiency study shows significantly reduced gold usage through local sustainable coating. Almost 100% material utilization is achieved, while gold spots geometry and position can be adjusted and replace the full surface electroplating coating.

Keywords: Laser-based gold coating; electrical contacts; gold wire deposition; laser micro deposition; environmentally friendly coating

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1. Introduction

The functionalization of sheet metal components is an integral part of many areas of production technology and enables reduced process times as well as increased vertical range of manufacture and reduced number of process steps through functional integration. In the production of electrical contact components, component-

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specific and production-related requirements are made with regard to optimal electrical such as almost loss-free contact properties. Therefore, stamped and bent sheet metal substrates are often used as a basis, which are functionalized for use as contact components by geometrical and surface-technical refinement (Doduco, 2020). For this, spring steel or copper materials are used as carrier sheet metal (Vinaricky, 2016). The bent and stamped sheet metal substrates are coated with an electrochemically deposited single precious metal layer or a layer system consisting of a base coating of metals such as nickel, tin, copper and a precious metal layer with gold, silver, palladium, platinum or alloys thereof to improve electrical conductivity and protect against corrosion (DGO e.V., 2020). The coatings optimize the components for low contact resistance, high wear resistance and avoidance of high-resistance oxidation layers through chemical reaction (ZVEI, 2020).

Depending on the process route, using electroplated pre-coated sheet metals leads to, among other things, coated stamping waste through the stamping-bending process, which has to be recycled at great expense. The layer-applying galvanic and chemical deposition of precious metal (alloys) is an energy-intensive and resource-inefficient process, which additionally emits cyanide compounds that are harmful to the environment (Umweltbundesamt, 2020). In terms of vertical integration, electroplating poses a further challenge to contact component manufacturers regarding continuous production lines, price dependency on companies for electroplating, and additional logistics. The ecological disadvantages of electroplating (polluted water and its treatment, disposal of toxic electroplating sludge as well as pollution in the air) are assessed by the German Environment Agency (Umweltbundesamt, 2020). In addition to electroplating, the state of the art includes physical vapor deposition PVD and other technologies such as welding and riveting of the contact components with suitable contact materials for functionalization of the sheet metal components (Doduco, 2020).

In contrast, energy- and resource-efficient processes will be required in the future for the sustainable production of gold-coated contact parts with a positive contribution to environmental protection. Alternative technologies, e. g. (Scheifenbaum, 2014) or (Fraunhofer ILT, 2009), are the subject of research, but have not yet been established on an industrial scale. In particular, the integrability into existing processes and their cycle rates of up to 2,000 parts per minute as well as the handling of the technology represent a challenge for the research field (Fritz Stepper GmbH & Co. KG, 2020). This paper aims to investigate an environmentally friendly and resource-efficient alternative to the electroplating of contact parts with gold. For this purpose, the application-specific gold coating has to be carried out by means of selective laser-based micro gold wire deposition. Wire-based coating materials offer advantages for process handling in press shop environments compared to other coating approaches that are currently being researched with electrolytes (Scheifenbaum, 2014; Fuchs et al., 2018) or powders (Fraunhofer ILT, 2009; Fraunhofer ILT, 2013). In addition to improved material utilization, the flexible functionalization technology aims at adjustability of the position-selective coating geometry. The system development of this functionalization approach on laser-based micro gold wire deposition as well as the process development carried out on the stated system are examined in detail below.

2. System development

The aim of the system-side development is the design of an automated stand-alone system for functionalizing punched sheet metal parts as electrical contact components. The functionalization thereby is implemented with a laser deposition of micro gold wires by means of local precious metal coating dots, which serves to substitute the environmentally harmful electroplating coating. Fig. 1 describes this goal and gives an overview of the realization concept. The approach described here is based on a system which can be integrated into the direct manufacturing process chain instead of the strip electroplating line and which acts as a separate, stand-alone system and can be linked to the higher-level machines.

The overall system consists of various individual components, which are the housing including laser safety, a guide and handling module for the punched strip, a wire head, the laser system and an optical inline quality assurance system. Based on the presented conception, the most important components are described below from a design point of view.

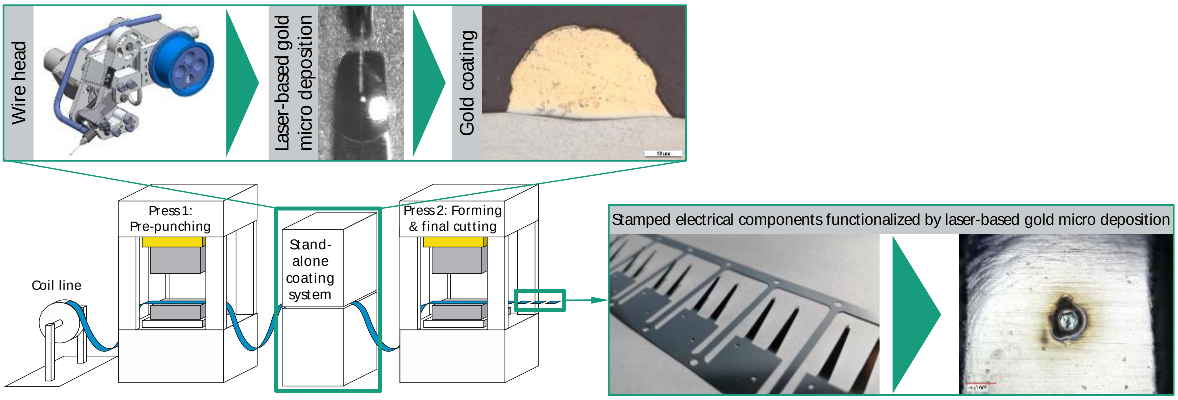


Fig. 1. Approach and realization

2.1. 5-axis wire head

According to the overall process concept, the wire is to be positioned by a precise module in a multi-axis manner relatively to the punched strip. For this purpose, a dynamic 3-axis system consisting of two linear motor axes for X and Y as well as a servo-motor spindle axis for Z is designed. The repeatability corresponds to ± 0.005 mm in each case and meets the requirements for the positioning accuracy of the dot to be welded on, which is quantified as ± 0.1 mm. An optimization with regard to short cycle times as well as easy handling and fast set-up time was carried out on the wire head. In order to make wire changes as easy as possible, the wire head is equipped with a laterally direct access to the wire spool and simple threading, see Fig. 3. Additionally, the wire spool holder is driven by a motor (T1 axis). Hence the wire can be unwound continuously into the supply loop, while the wire is fed at the welding cycle through a pair of rollers (T axis).

Possible processable wires are on the one hand round wires with Ø 0.02 mm up to Ø 0.4 mm or flat wires with 0.1 x 0.01 mm² up to 0.125 x 0.04 mm². Initially, however, the challenge are the bendable wires at the lower specification limit. Due to the very short free bending length, a closed guide is required right up to the coating point. The wire guide is thereby developed with a small tube. Due to the relatively high frictional force within the guide, an active friction minimization method is additionally developed to facilitate feed and prevent the wire from buckling due to friction.

2.2. Sheet metal handling

Since the electrical contact components are pre-punched but still on the punching strip, the coating is to be done on the continuous punched strip. In this process, the components and the strip have punched holes which are used for two-dimensional alignment. These holes are also to be used here for referencing the components, whereby a flat support must also be ensured in the area of the coating workspace.

The sheet metal handling and the feed movement are designed as a fully automatic pneumatic gripper feed, see Fig. 3. With this it is possible to advance the sheet within 150 ms. The sheet feeding system essentially consists of three pneumatic cylinders (one feed cylinder, one static and one dynamic clamping cylinder) and an adjustable sheet guiding system. The dynamic clamping cylinder is mounted on the carriage of the feed cylinder, which in turn clamps the sheet metal by means of a rotationally symmetrical hold-down device. Furthermore, the handling of continuously punched components on the strip requires openings in the (laser safety) housing. Against the background of laser safety, the sheet handling therefore includes a uniform strip running plane (focal level acc. to the laser system design) as well as a beam trap on the outside of the machine.

2.3. Laser optical concept

The main tool for the process is the laser system consisting of the components as shown in Fig. 2. In the underlaying concept, a post-objective scanning approach is chosen. Refocusing is performed via a focus translator system. Here, the laser beam is expanded by a lens moving along the optical axis and focused onto the processing level by means of a subsequent collimation/focusing system. The lateral deflection in X and Y is achieved by two moving galvo mirrors, whereas the focus of ±3 mm is motorized adjustable by means of Z-translator, see Fig. 2. The total realized field size is 40 x 40 mm².

The laser source used for the project is an IPG-YLR-250-SM fiber laser with a center wavelength of 1075 nm and a laser output of 250 W. In addition, a combination of CCD camera and corresponding lens is coupled to the same beam axis. Thus, the alignment of all individual systems in setup mode as well as inline process monitoring is enabled analogously to the scanner beam position.

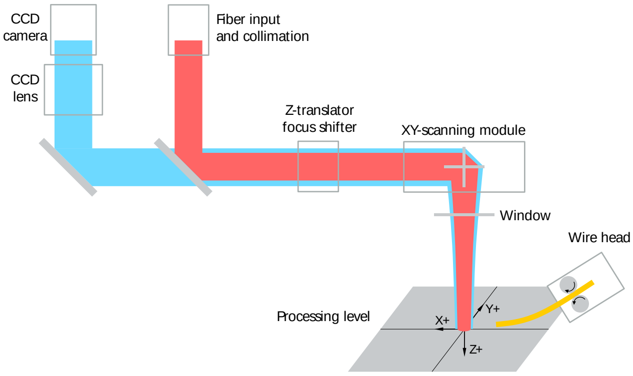


Fig. 2. Schematic representation of the laser optical concept

2.4. Complete stand-alone system

Fig. 3 shows the final structure of the system, as it was also used for the subsequent process investigations in the following chapters. The machine housing is the basis and at the same time guarantees laser safety class 1 due to the complete encapsulation of the modules. Only the feed-through of the punched sheet metal strip requires two openings, which are ensured in accordance with the descriptions in chapter 2.2. The sheet metal strip is guided through the system (sheet metal guide) from right to left along the functionalization process chain. This is passed under the laser system, whereby the 5-axis wire head operates within the laser processing area. Then the pneumatic sheet feed is positioned, which advances the coated electrical components directly into the inline quality assurance system. The system from Harms & Wende QST uses two cameras to take images after every second coating cycle and analyzes them with regard to the real number and absolute position of gold dots on the component, as well as the diameters of the gold dots. A comparison with the target template leads to the detection of quality deviations. The sophisticated system makes it possible to detect the small dots with diameters of 100 – 300 µm on the base surface of the entire component and, on the other hand, to achieve sufficiently good illumination through several coordinated light sources. The active feedback of the component state is transferred in binary form (component OK or not OK) and passed on to the main machine control. Detailed measurement and quality parameters, on the other hand, are saved for later evaluation. After passing through the quality assurance module, the strip exits the stand-alone system and can either be wound up for further processing or fed directly to the downstream process.

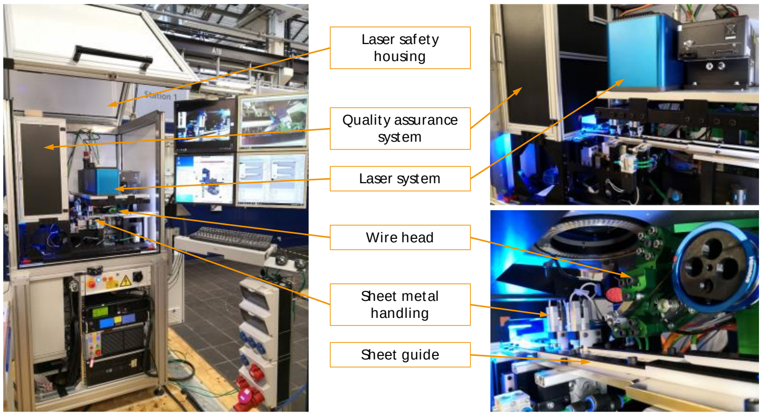


Fig. 3. Final mechanical setup of the stand-alone system

3. Process development and experiments

3.1. Demonstrator approach

In the underlying work, a validation approach with two different demonstrators is chosen. The design of the first demonstrator component is a sliding contact spring with a spherical tip that is defined as representative of a typical product for applications in electrical connection technology, which are classically manufactured by stamping, see Fig. 4 a). The surface to be coated here is in the area of the two fingers with the embossed spherical tip. One gold dot each should be coated here. The second demonstrator corresponds to a snap dome, whereby this has four small embossed tips in a convex design and a large embossed dome of a concave design, see Fig. 4 b). One gold dot is to be coated on each of the four convex surfaces and one on the concave surface.

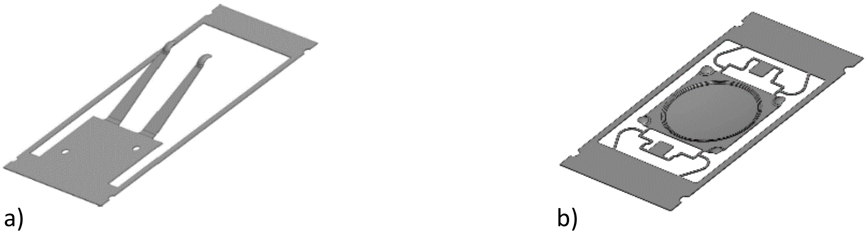


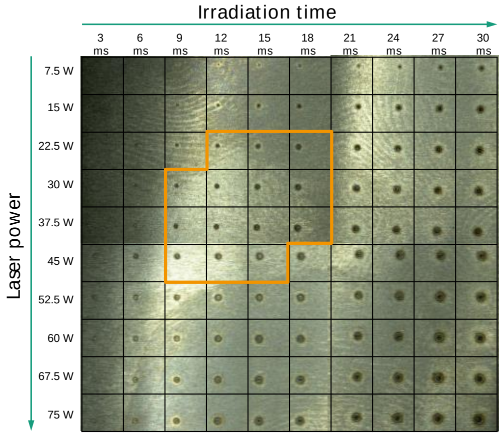
Fig. 4. Demonstrator component. a) Sliding contact spring with 2 fingers (Carl Dillenius). b) Snap Dome with connection pints (Inovan)

The basic material used for both is an austenitic stainless steel stamped strip made of 1.4310 (X10CrNi18-8) with a strip width of 40 mm and a sheet thickness of 0.1 mm. The footprint of the demonstrator components is set at 40 x 20 mm². Analogous to conventional electroplating with precious metals, the coating material in the present paper is defined as gold. Micro gold wires with a rectangular cross-section of 20 x 100 µm² and with a purity group of 4N (99.99% Au) are used. Compared to round wires, flat wires allow reduced directional reflection due to the surface curvature of a round wire.

3.2. Process parameter

As part of the process development, an impact analysis is first carried out in order to identify the main parameters that need to be varied. The laser power and the duration of irradiation are the primary parameters in the scope of this paper. To delimit the welding parameter window, a study is carried out on the energy input in the substrate for various welding parameters. A preselection of possible parameter combinations (laser power and irradiation time) for subsequent coating by means of small welded dots is indicated based on the size of the laser marks. Targeted diameters of the later coating dots are 100 to 300 µm. The energy input study therefore shows that the laser power should be in the range of 22.5 to 45 W and between 9 and 18 ms irradiation duration. The exact specification can be seen in the orange marked area in Fig. 5 left.

In addition, the defect patterns during the laser-based micro wire deposition process are specified within preliminary coating trials, see Fig. 5 right. In comparison to a continuous welding process, the coating process requires a relatively low energy input in order to avoid excessive mixing of the melt bath (defect pattern 5) and to avoid generating too large heat-affected zones or melting points. However, there is a direct interaction between defect patterns 1 to 4, in which the wire is not welded due to the low energy input. This results in drop formation, folds or separated wire residues or welding beads. Moreover, one of the most probable process errors is the connected wire to the deposited dot after finished laser process. These error patterns, in particular No. 6, will be discussed again in the further course, whereby appropriate precautions and countermeasures for subsequent optimization studies can be defined on the basis of this error description.



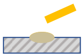
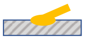
No.	Schematic	Error description
1		Drop formation
2		Wire folding over
3		Cutting the wire
4		Gold dot on surface, but not welded
5		Mixing of the melt bath
6		Wire connected to the dot

Fig. 5. Left: Energy-Input-Study and preselection of welding parameters. Right: Description of defect patterns during coating process.

After numerous test series, the laser process could be adjusted that way, that the gold dots are connected in the best possible way by welding metallurgy, but at the same time have a high degree of purity, especially on the surface of the dot-shaped gold coating. In accordance with the design of the system technology and the concept for integrating the stand-alone system into existing processes, the components were coated successively on the punched strip. Although the process development was carried out on both demonstrators, only the coating of the sliding contact springs will be presented in this paper. The parameters, however, are the same for both demonstrators due to the same base material and the same substrate geometry and can therefore be transferred. Hence, the process parameters for best suited coating results are the following:

- Laser Power: 30 W
- Irradiation time: 10 ms
- Welded wire length: 1.5 mm (0.8 … 2.5 mm for dot size variation)

As a result of the process development, Fig. 6 shows the coated sliding contact springs located on the strip. A selection of individual coating points is shown by light microscope image.

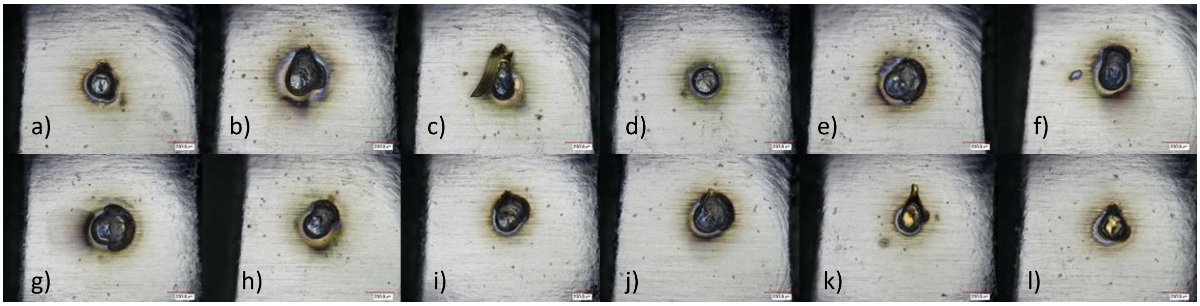


Fig. 6. Coated sliding contact springs. Top: Single coating dots a) to l). Bottom: Components on the sheet metal strip.

The top view shows that there is currently still a fluctuation in the process stability. The deposited coating dots a), d), k) and l) have been applied exactly at the target position and are uniformly round. With reference to the defect pattern description in Fig. 5, it could be determined that defect patterns 1-4 lead to incorrect welding. Furthermore, irradiation of the gold wire that is not exactly centered leads on the one hand to a laser-marked dot on the substrate and on the other hand to a somewhat eccentric welded-on coating gold dot, see Fig. 6 b) and e) to j). Nevertheless, the gold dots are applied properly, as will be visible in chapter 3.3 below. As mentioned in the procedure, the welding of the wire (connection) to the gold dot also has a share in the results and is due to the very low laser melting energy introduced. The dots c), k) and l) are an example of this, where the wire was then subsequently separated from the melt bath or from the dot.

3.3. Evaluation and gold spot analysis

In accordance with the coated demonstrators described in chapter 3.2, a detailed evaluation of the coating by means of metallographic micrographs and EDX will be performed in this chapter. The aim is the qualitative investigation with regard to the welding metallurgical connection of the gold dots to the substrate as well as the quantitative evaluation of the gold dot geometry and the spatially resolved purity in the coating gold dot.

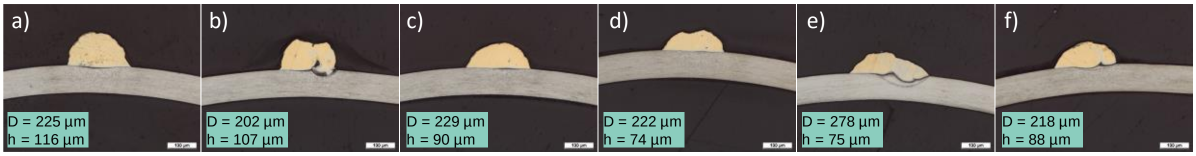


Fig. 7. Selection of micrographs of coated sliding contact spring demonstrators

First, the geometric characterization of the gold dots in the micrograph is carried out, whereby the dot diameter D and the dot height H are measured. The diameter is measured from the outer edges of the dot in the section. If these two points are connected with a virtual straight line and the distance to the highest point of the gold dot is measured perpendicular, the dot height is obtained. For selected gold dots, the measured values can be found in Fig. 7, while the mean diameter is $D = 229.0\ \mu m$ and the mean height is $h = 91.7\ \mu m$.

Statements about the welding metallurgical connection of the coating dots can now also be made via the micrographs. It can be seen that dots a), c), d) and f) exhibit a low degree of intermixing of the melt bath at the base of the dot. A good connection can be assumed here, whereby the advantageous properties of the precious metal are retained. With dots b) and e), however, a clear intermixing can be seen. Here, further analyses have to be carried out with regard to functionality. Furthermore, micrograph e) shows a coating dot which was created by off-center irradiation, clearly recognizable by the gold dot seated on the left and with strong penetration to the right with a high degree of mixing.

In addition, the micrographs of four gold dots were examined for the metallic composition using a scanning electron microscope, SEM and energy dispersive X-ray microanalysis, EDX. The results show a very high purity of the gold dots. The exact values can be found in Fig. 8. In summary, the following values can be achieved:

Table 1. Mean mass percentage gold content of EDX-analysis

Mass percentage gold in $m\%\ Au$	Top surface	Center	Bottom
Minimum	86.22	91.60	30.28
Average	97.92	96.54	53.78
Maximum	100.00	100.00	85.62

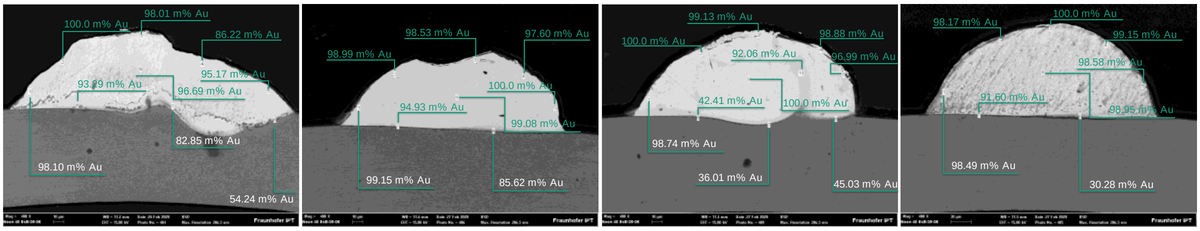


Fig. 8. Results of the metallographic examination by SEM and EDX

On the top surface of the gold dot, an average mass gold content of $97.92\ m\%\ Au$ can be reached. Similarly good values are achieved in the center of the det with up to an average of $96.54\ m\%\ Au$. However, the low gold content at the base of the point with averaged $53.78\ m\%\ Au$ shows the welding metallurgical connection by means of local limited intermixing and is therefore an indicator of the successful welding of the coating dots. The occasionally high gold proportions in the ground are to be examined further and will be analyzed separately by means of further elaborations.

4. Result validation and resource efficiency analysis

In addition to the environmental improvements resulting from the novel innovative functionalization process, there are also savings in gold consumption and thus a reduction in costs. From the previous chapters, average geometric values of the gold dots with a diameter of $D = 229\ \mu m$ and a height of $h = 91.7 \mu m$ can be determined. These now serve as the basis for considering resource efficiency. Fig. 9 composes the average volume of gold required according to the following equation.

$$V = \frac{\pi}{6} h(3R^2 + h^2) = \frac{\pi}{6} h\left(\frac{3}{4} D^2 + h^2\right) \tag{1}$$

With the process aimed at in this paper, a volume per dot of $V_P = 2.29 \cdot 10^{-3}\ mm^3$ is coated. At a gold price of 1,628.36 € per troy ounce, the volumetric gold price is 1.01 €/mm³. In the following, the savings are extrapolated to a case study of a component series with 5 million manufactured contact components.

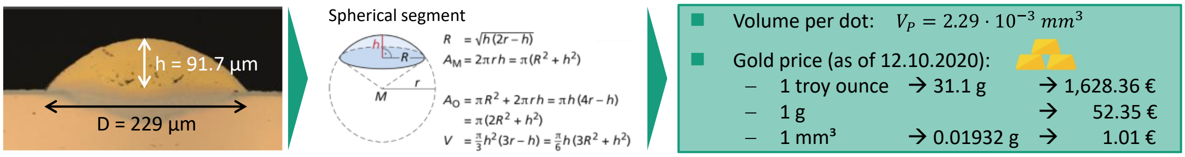


Fig. 9. Calculation of gold dot volume and gold cost

As an adequate comparison of use of resources and costs, this coating technology and the brush technique are to be compared for the sliding spring contacts. Due to the protruding contact tips, the brush technique is usually the most suitable process and is considered to be cost-optimized for this application. Typically, somewhat thicker, more wear-resistant precious metal layers between 2.0 and 5.0 µm are used on the tips (Fig. 10). Conventionally, the gold cost per component is 1.212 cents for 2 µm coating layer thickness and 3.051 cents for the 5 µm layer thickness with the conventional brush technique. In comparison, the gold costs with the underlying technology are 0.46 cents for a component with two gold dots. This corresponds to a cost reduction of ≈ 62.1 % up to 84.9 %. Extrapolated to 5 million manufactured components, this corresponds to savings in gold worth between 37,600 € and 129,550 €.

The snap dome is normally coated with the selective technique. Up to now, three 4 mm wide strips have been selectively deposited on the snap dome by means of strip electroplating in order to coat both, the contact for the pressure point in the middle and the contact points in the corners. With the innovative functionalization process, 5 gold dots are planned, four in the corners and one in the middle. Inovan coats comparable components with a gold layer thickness of 1.0 µm, see Fig. 10. This resulted in a gold volume with the conventional coating process of $240 \times 10^{-3}\ mm^3$ and gold costs of 24.24 cents per component. In comparison, the same component with laser coating only requires a gold volume of $11.45 \times 10^{-3}\ mm^3$, which corresponds to 1.156 cents per component. This results in savings of 23.083 cents per component and thus a cost reduction of 95.2 %. On 5 million components, this corresponds to a saving of 1,154,150 €.

A particular potential for savings can therefore be demonstrated in the case of large, flat components with distributed contact points and different surface curvatures.

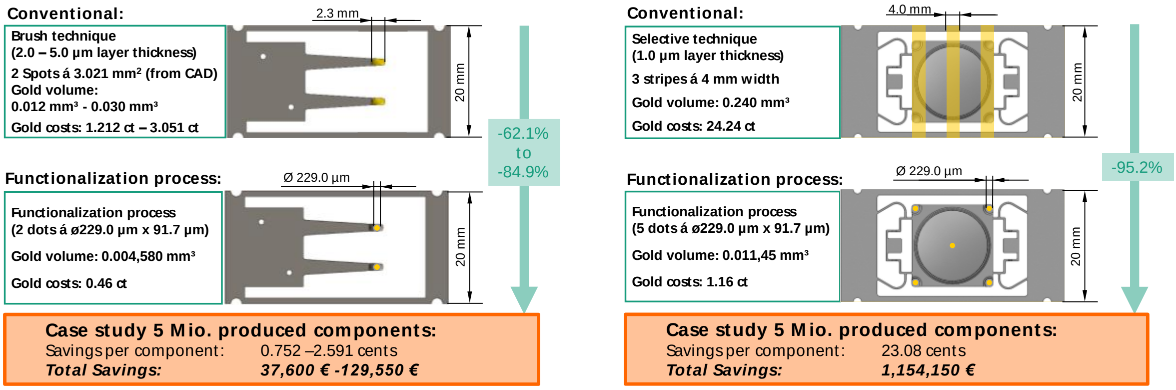


Fig. 10. Evaluation of resource efficiency on demonstrators by functionalization process. Left: Sliding contact spring. Right: Snap dome.

The economic feasibility study was primarily based only on the reduction in gold consumption and the associated reduction in material costs. Other costs, such as those for logistic processes between the stamping and electroplating shop, the electroplating process itself, for the disposal and treatment of chemical waste, as well as energy costs and the effort required to protect employees and the environment from toxins were not taken into account. Factors such as constant availability through process integration and independence from supplier prices (electroplating) through in-house gold plating are also not considered. Finally, stamping waste, which is coated with gold and normally has to be recycled at great expense, is also no longer generated.

5. Conclusions

With the developed system for the functionalization of electrical components on the punched strip, it was possible to prove significant ecological and economic advantages, especially compared to conventional coating processes such as electroplating. The stand-alone system designed for this purpose, with its highly dynamic 5-axis wire head, laser system, automated sheet feed and inline quality assurance, offers a complete module that can be integrated into existing process chains. As part of the process development, it could be shown that the coating can be applied precisely in the required area with electrical contact using laser-based micro wire deposition and thus does not waste precious metals. In this process, laser irradiation takes only 10 ms. With gold dots averaging 229 µm in diameter and approximately 72 µm in height, the new technology offers significant cost savings. Using two demonstrators, it could been shown that 62 - 85 % gold can be saved. The technology is particularly suitable for large-area components with multiple distributed, flat contact points. Here, even up to 95 % gold can be saved, since there is no more gold-coated stamping waste. Due to the particularly noteworthy environmental relevance and increased resource efficiency of laser-based gold micro wire deposition, as well as the proven potential for precious metal savings, the technology represents a motivation to continue the work, both in terms of resource and cost efficiency as well as the environmental relevance of the technology. Further research is required, focusing in particular on optimizing the process and system technology, as well as increased output and shorter cycle times for application- and speed-oriented integration into the process chain.

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