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Multi-material Functional Integration with Combined DED Additive Manufacturing Processes

Under the project lead of the Edag Group, two demonstrators were realized with the additive manufacturing process known as Direct Energy Deposition using wire and arc and powder and plasma. One was a see-through A-pillar and the other a motorcycle handlebar with electrical and hydraulic conduits integrated into the structure.

The demonstrators set up under the leadership of Edag have the task of showing the potential of multi-material concepts of additive manufacturing for better functional integration in vehicle components. The see-through A-pillar is a revolutionary design that solves a long-standing vehicle safety issue: blind spots caused by bulky A-pillars. The result is a better driver's view of the road, which in turn improves passive safety on curves, roundabouts, pedestrians and cyclists crossing, and junctions. The functional motorcycle handlebar is an outstanding development that responds to the need for more design and customization in motorcycles. It enables the integration of electrical (cables for example for lights, indicators or starter) and hydraulic (brake, clutch) requirements into the handlebar structure, eliminating the need for visible cables around the handlebar.

DESIGN GUIDELINES FOR DED-ARC

To achieve the design goals of increasing the field of view and integrating functions, it was necessary to push the limits of manufacturing restrictions. Edag, in cooperation with Lortek, has developed design guidelines for the Direct Energy Deposition (DED) manufacturing process applying wire and arc (DED-Arc, also known as WAAM: Wire Arc Additive

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Manufacturing) through extensive testing, targeting a minimum wall thickness of 2.5 mm and cantilever angles of up to 50° from vertical. To achieve this, surface-defined models are required, while volumetric bodies must be included at vertical wall intersections for reliable processing. There should also be no wall thickness variations. At joints (L-/T-shape) it is necessary to integrate gaps at the upper ends in the build-up direction of such geometries on vertical walls in the design to achieve optimum build-up quality. Actual 3-D geometry in solid regions should be avoided, structures should end with flat edges, not pointed tips. It is important to note that the consistent achievement of the desired 2.5 mm wall thickness by DED-Arc and 1 mm wire feedstock is still challenging. The feasibility of achieving this thickness depends on several factors, including the equipment and materials used, so it is imperative that such limitations are considered in the manufacturing process.

A-PILLAR DESIGN

The challenge in designing the A-pillar was to balance the conflicting goals of maximizing visibility while maintaining crash safety. This required extensive iteration and crash simulations. Using Synera software, an automated engineering approach that optimizes rib-like structures for crashworthiness was implemented, reducing manual effort and meeting design guidelines at each design step and iteration. This results in realizable designs in a comprehensive time frame. Both small overlap and roof crush crash simulations were performed using the generated Generalized Incremental Stress State dependent damage Model (GISSMO) material card for the Bohler EMK8 material used.

MANUFACTURING AND FUNCTION INTEGRATION OF THE A-PILLAR

A new clamping tool was developed by Lortek for the DED-Arc process, with which a double-sided print can be realized on a build plate for direct use of this plate in the component, **FIGURE 1**. The blue part is the build plate, while the gray parts are produced using the DED-Arc process. Six A-pillars were realized with different designs, one was finished with sandblasting, partial milling (only required at the connection points to related parts of the body, most of the component remains in the raw state to minimize costs), cathodic dip coating (KTL), integration of conventional conductors, painting, and assembly.

For the integration of the conductive wire, a defined groove was introduced into the design, the wire (in this case a data transmission CAN bus cable, but other configurations are also realizable) was inserted and fixed and coated with zinc using the Atmospheric Plasma Powder Deposition (APPD) process as another DED application to create a monolithic structure, **FIGURE 2**.

Further studies to print CAN-capable conductors directly into the steel structure in a layer-by-layer configuration using the APPD process were conducted. It turned out that to achieve the required characteristic impedance of 120 Ω, a comparatively large spacing between the conductors would be required, so the thickness of the insulator would have to be 1.5 mm, which is not feasible using APPD with a conductor width of 338 µm, a thickness of 35 µm, a spacing of 605 µm and a relative dielectric constant of 9. In addition, the APPD-generated layers cannot withstand the KTL process due to their porosity. Therefore, APPD layers must be added after KTL.

MULTI-FUNCTIONAL MOTORCYCLE HANDLEBAR

The higher level of functional integration was realized on the motorcycle handlebar since all external cables for electrical signals and hydraulic pressure were substituted by integrated conduits. The main manufacturing strategy involved a stepwise approach, starting with the DED-Arc process generating a first, hollow part of the half final span of the handlebar. The basically triangle-shaped cross section was chosen to save mass and provide a basis for the application of the APPD for the creation of insulated conductor tracks. **FIGURE 3** shows this shape in red color, with two vertical ridges added as boundaries for the powder deposition and as starting points for the later DED-Arc procedures, respectively.

During the layer-by-layer DED-Arc manufacturing a water-cooling jacket was applied which was manually adjusted so that it was always

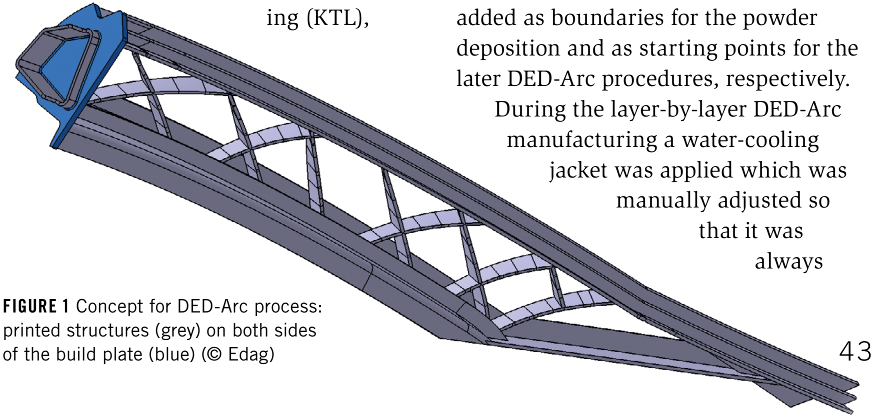

FIGURE 1 Concept for DED-Arc process: printed structures (grey) on both sides of the build plate (blue) (© Edag)

FIGURE 2 Imprinted CAN bus cable into the KTL coated DED-Arc printed A-pillar using APPD (© Inocon)

close to the current level of the increasing height of the additively manufactured handlebar parts. By machining, the U-shaped geometry was realized in tighter geometric tolerances than DED-Arc usually offers. Underlying investigations had previously shown that the application of APPD layers to the as-built surface easily leads to breakage of the ceramic layers.

The generation of insulated conductor tracks starts with a layer wise APPD-based deposition of several single layers of aluminum oxide powder (using powder with median particle size distribution D$_{50}$ of 17,3 µm, powder size range 8 to 32 µm), covering the full width between the webs along the full span of the conductors. After changing feedstock to pure copper (particle size ranging from 8 to 12 µm, D$_{50}$=10 µm), APPD was applied to deposit layers of copper up to total height of 1 mm. By varying the masks, covering the areas onto which no coating had to be deposited, the generation of a nine-layer approach was finalized, being again an important achievement from the cooperation in the EU-funded Multi-Fun project.

The resulting five copper conductors – each insulated by aluminum oxide to themselves and the first aluminum part – were subsequently covered by aluminum layers, again using the DED-Arc process. During these operations, the hollow shape was used as an intrinsic cooling channel, transferring excess energy to the surrounding. Therefore, the deposition rate can be increased while reducing the amount of distortion.

The entire process of integration of conductors is shown in **FIGURE 4**: realizing half of the handlebar with DED-Arc, then milling a channel for conductor integration, followed by adding isolators and conductors in a step-by-step approach and covering with DED-Arc process as last step.

The second functionality to be integrated – the transmission of hydraulic pressure – was manufactured by milling with special burr types. The opening of the tool's shaft is afterwards tightly closed by applying wire arc welding. Similarly, the middle section, the handlebar clamps as well as connectors to the standard controls are created in the same hybrid way, layer wise adding solid material and final subtractive machining. Adhesive bonding was chosen to be used for the joints between the outer sections of the handlebars to parts machined from standard tubes as well as the final assembly to the middle section. The full handlebar with included conductors and attached cables for connecting the controls can be seen in **FIGURE 5**.

MATERIAL PROPERTIES OF THE MOTORCYCLE HANDLEBAR

AlMg0.7SiTiB was chosen as the aluminum alloy for the mechanical structure of the handlebar, as it is similar to the standard AlMgSi alloys used in conventional handlebar production and is available as a wire electrode. The supplier of this MA-6063 feedstock, Migal.co, is stating the range of 200 to 260 MPa as the yield strength, 250 to 280 MPa for the ultimate tensile strength as well as the elongation until failure with 6 to 12 % (all values valid in peak aged condition).

The main requirements for the embedded, insulated conductor stacks were twofold: the insulating coating based on aluminum oxide had to provide electrical insulation for low voltage signal transfer while the deposited pure copper had to substitute drawn cables. The electrical insulators and conductors were evaluated against short circuiting as well as conductivity, respectively, in the as-deposited condition, after integration into the structural aluminum part as well as after standard peak age heat treatment of the multi-material part (540 °C/1 h + 180 °C/8 h). The main finding of these investigations was the positive effects of DED-Arc itself and subsequent conventional Heat Treatment (HT) on the electrical resistance of the powder-based conductors; while the copper tracks showed an aver-

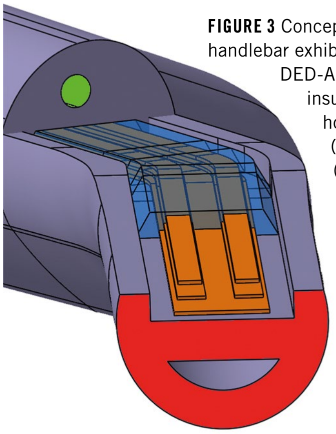

FIGURE 3 Concept of the multi-functional motorcycle handlebar exhibiting the cross section of the first DED-Arc part (red), conductor tracks (orange), insulator coatings (blue) as well as the hollow channel for hydraulic actuation (green circle at the top) (© Edag)

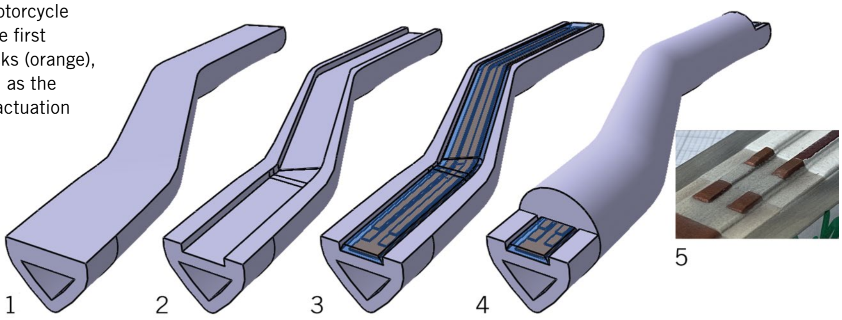

FIGURE 4 Stepwise integration of isolators and conductors (from left to right): realizing half of the handlebar with DED-Arc, milling a channel for conductor integration, adding isolators and conductors in a step-by-step approach, and covering with DED-Arc process (© Edag | LKR)

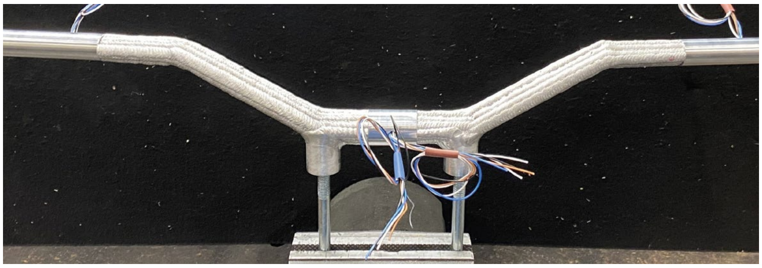

FIGURE 5 Motorbike handlebar demonstrator (© LKR)

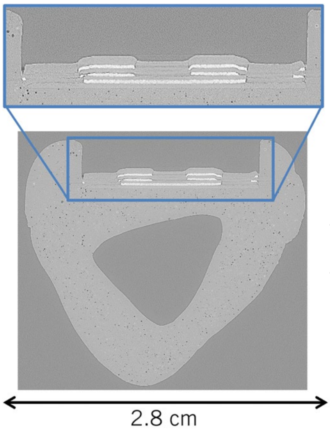

FIGURE 6 Section cut of conductors-isolators-stacks on top of a DED-Arc structure, analyzed with a Synchrotron Large Hadron Collider (LHC) (© DLR)

age of $0.06\ \Omega*\text{mm}^2/\text{m}$, the numbers dropped after DED-Arc and final HT to $0.038\ \Omega*\text{mm}^2/\text{m}$ and $0.028\ \Omega*\text{mm}^2/\text{m}$, respectively.

Although these values were still approximately 1.7 times higher than the definition of pure copper in the International Annealed Copper Standard (IACS), they also showed an improvement by a factor of 2.7 as a result of the heat treatment. Hohm et al. [1] reported further optimization potential, with the lowest values being achieved at a level of 1.33 IACS.

TESTING

Functional tests were conducted successfully on both types of functionalization. On the A-pillar, the material card was developed from sample tests and three-point-bending tests were carried out on the whole structure showing a quite ductile behavior leading to higher energy absorption in crash case. The structural stiffness and strength are in a comparable range to conventional behavior of A-pillars consisting of steel sheets.

To gain insights into the microstructure of the steel material of the A-pillar showing a comparable low porosity <0.1 %, Synchrotron testing was conducted. This was also conducted on the functionalized motorbike handlebar showing that especially the isolators are continuously separating the conductors from each other and from the bulk material, **FIGURE 6**. The brittle alumina isolators even fulfill their task to separate the conductors from each other in case of breakage due to long-term fatigue testing.

CONCLUSION

In the case of the transparent A-pillar, it was possible to integrate conventional cables with zinc powder using the APPD process on an attractive DED-Arc steel structure, pushing the limits of passive safety in passenger cars. A monolithic component was developed that can contain conventional cables. The printing time for the entire component is only about 10 h, with the possibility of automating the process to further industrialize it.

The integration of five pure, partially stacked copper conductors and Al_2O_3 ceramic as insulation material using the APPD process in a DED-Arc-manufactured structure made from a 6063 aluminum alloy was demonstrated on the motorcycle handlebar. Thus, the necessary properties for riding a motorcycle with this innovative handlebar can be achieved with all functions being integrated into the component.

REFERENCE

[1] Hohm, D.; Gradinger, R.: Electrical treatment of thermal sprayed copper layers to improve the electrical conductivity. Metal Additive Manufacturing Conference, Vienna, 2023

THANKS

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