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New Materials and Processes for Transport Applications: Going Hybrid and Beyond

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The present text introduces a Special Section of Advanced Engineering Materials linked to the symposium Advanced Materials for Transport Applications organized by the authors within the framework of the EUROMAT 2017 conference. It introduces the contributions that make up this Special Section, and takes the fact that a majority of them is related to the broader topic of hybrid materials and structures as a motivation for a short overview of this exciting area of research.

1. Introduction

Transformation is nothing new to the transport industry at large, but if there is any constancy at all in this sector, it is the quest for lightweight design solutions.[1,2] E-mobility, which has certainly rocked the foundations of the automotive industry and is just starting to open up new perspectives in aerospace and maritime engineering, has all but changed the persistent interest in ever-lighter structural solutions. The present Special Section of Advanced Engineering Materials is dedicated to this development and at the same time linked to a symposium on "Advanced Materials for Transport Applications" held for the 5th time since 2009 within the framework of the biannual EUROMAT conference, the European Congress and Exhibition on Advanced Materials and Processes. In 2017, the city of Thessaloniki hosted this event from September 17th to 22nd, bringing together more than 2300 scientists representing 65 countries.[3]

The Special Section brings together selected papers from the aforementioned symposium. The majority of these focus on lightweighting, and again many of them on understanding, designing, modeling, simulating, processing, and characterizing of hybrid materials and structures meant to support this aim. This apparent concentration on multi-material and hybrid solutions has motivated us to dedicate this introductory essay to this topic.

Hybrid materials and structures are an expression of the notion that engineering design should strive to place every material, where best use is made of its specific characteristics: A notion which effectively support development of multi-material structures.

The recognition of this idea in the academic as well as the industrial sector can be derived from several indicators: In Germany, the research priority program SPP 1712 funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) addresses the development of hybrid materials and structures from a fundamental research perspective. Among its predecessors are again DFG-supported research units like FOR 1224 on CFRP-Aluminum Transition Structures in Lightweight Design. Also German, but oriented toward higher technology readiness levels (TRLs) and actual application is a long term research framework program initiated by the Federal Ministry of Education and Research, HyMat, which aims at "new possibilities, new market potentials" to be unlocked by this class of materials. Originally published in autumn 2017, the program issued its first calls in the second half of 2018.

In the following sections, we will contrast the many definitions of hybrid materials and structures, provide examples of these as well as of their applications in the transport industry, and link such generic information to the concrete research covered by the articles that form the main body of this Special Section. Finally, we will present future trends in lightweight design we deem important for the transport industry. We close with an outlook on the coming EUROMAT conference, which will see both a continuation and an extension of our activities in 2019.

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2. Hybrid Materials and Structures

2.1. What's in a Name?

The research area of hybrid materials and structures suffers somewhat from a disambiguation problem. There is, actually, more than one definition around for what a hybrid material is.

One of these is linked to length scales, characterizing hybrid materials as materials showing nano- rather than micro- or meso-scale structuring, where structuring is to be understood as reflecting the primary feature size of the constituent materials. According to this definition, a further requirement any claimant to the designation has to meet is the emergence of new properties which deviate from those of the constituents. On this latter point, a somewhat questionable distinction from nanocomposites is based.[4] The set of materials covered by this definition is clearly dominated by functional rather than structural materials.

A definition closer to lightweight design is proposed by the aforementioned Priority Program SPP 1712, which suggests the term intrinsic hybrid for describing a multi-material engineering component in the production of which the joint between the dissimilar materials is created in the course of the primary or secondary shaping operation, thus avoiding subsequent, separate joining operations. As candidate materials, metals and endless fiber reinforced composites are named.[5]

A similar line of thought, though broader in terms of the actual materials combined, is suggested by J. Hausmann, M. Siebert, and A. von Hehl in their welcome address to the 2018 conference on Hybrid Materials and Structures at Bremen (April 18th and 19th): "Innovative materials frequently act as trailblazer for the introduction of new materials and products. In many case, high performance components cannot be designed any more based on a single material. [. . .] To fully exploit the characteristic properties of a material, in the design of lightweight structural components, combining different materials becomes essential. Wherever this combination is realized by means of inseparable joints, we call the result a multi-material design, or a hybrid structure."[6]

The attentive reader will have noticed that this definition does not require a material combination spanning different material classes. It is thus not surprising that the conference also offered a session on multi-metal design, a move away from the common perspective that a hybrid should be considered as such only if at least two different material classes were combined, as implied by the HyMat research initiative, toward further stressing the process-oriented view introduced by SPP 1712. In contrast to this, the German Materials Society's (Deutsche Gesellschaft für Materialkunde e. V., DGM) technical committee on hybrid materials and structures specifically focusses on combinations of metals and composites.[7]

Fortunately, this essay is not required to decide among these definitions. Instead, we opt for the largest possible variety in the overview of hybrid materials and structures, that is, to follow.

2.2. Examples: Materials, Structures, and Applications

2.2.1. Materials & Structures

Figure 1 presents examples of hybrid materials and structures reflecting different TRL levels.

Undoubtedly a hybrid material is GLARE, a so-called fiber-metal laminate (FML) characterized by a build-up combining alternating layers of aluminum foil and glass fiber reinforced plastics (GFRP), with the metal providing the skins. GLARE and other FMLs excel thanks to a combination of improved impact (relative to the composite) and fatigue strength (relative to the metal). Since the introduction of GLARE, several other variants of FMLs have been suggested and studied, including high strength variants like TiGr combining titanium alloys and carbon fiber reinforced composites (CFRP),[8–10] aluminum/CFRP or steel/CFRP materials,[11] and combinations of magnesium with GFRP layers.[12] In terms of reinforcing fibers, besides glass and carbon, for example, basalt, aramide, polypropylene, or ultra high molecular weight polyethylene as well as different kinds of natural fibers have been considered.[10,11] Altogether, this variety of base materials in combination with the possibilities different layups, layer thicknesses etc. offers great potential to adapt FMLs to specific use cases.

Besides metal foils, wire meshes may also be used to improve the properties – specifically the damage tolerance – of fiber reinforced polymers, and at the same time endow them with a shaping option comparable to hot forming especially when thermoplastic matrices are employed. A material of this type is depicted in Figure 1b and has been described in detail by Hasselbruch et al.[13]

Combinations of polymers with reinforcing metal components produced by overmolding of the metal in a polymer injection molding process tend to be neglected in the discussion of hybrid materials and structures, though they'd conform to a number of the above definitions. A possible reason is the fact that they have long since entered a stage of commercialization. A special example of this kind of structure in which the injection molding step is used to provide stiffening to the materials joined, while at the same time providing the physical link between metal and CFRP parts is depicted in Figure 1e.

In contrast, otherwise similar combinations of different metals which replace the polymer injection molding with some casting process remain an object of research. Structures of this kind have been commercialized under the designation Varioustruct, a typical example being a sheet metal (typically steel) based beam like structure of convex cross section which is reinforced and stiffened by high pressure die cast aluminum ribs, with the joint between steel and Al created via the HPDC process and deriving its strength mainly from form fit and lesser contributions from force fit and metallic joints.[14] In general, improving reproducibility and performance of the latter remains a primary research objective which has, for example, been addressed by Schwankl et al. and Fang.[15–17] An application-oriented case study on steel-aluminum compound casting has been published by Schittenhelm et al. looking at a local reinforcement of a rear longitudinal carrier via a completely embedded steel structure: The resulting hybrid component offers high stiffness at reduced volume and may thus be interesting for applications with limited availability of space.[18]

Casting, for that matter, is not limited to producing metal-metal hybrids: Even combinations of cast metals and fiber-reinforced polymers (both GFRP and CFRP) have been realized at prototype level, using either metal casting processes like high (see Figure 1c) or low pressure die casting (LPDC, see Figure 1d) for creation of the hybrid,[19,20] or polymer injection molding, which besides establishing the joint serves to realize part of the geometry of the component depicted in Figure 1e. Possibly even more demanding is the integration of electronic components in high pressure die casting, as is exemplified by Figure 1f, which shows an HPDC component with integrated radio frequency identification (RFID) device, which may serve part identification in general as well as specific tasks like counteracting plagiarism. The concept as such, that is, integration of smart systems in HPDC, can also be extended to the use of sensors for monitoring tasks and may gain additional interest in a smart manufacturing and/or Internet of Things context.[21–23] Besides, it can also be transferred to Additive Manufacturing for metallic components,[24] and much more easily to polymer-based materials and structures, as is widely illustrated, for example, by structural health monitoring (SHM) approaches in the aerospace or wind energy industry.[25]

Obviously, there are several other possibilities to produce metal-metal hybrids. On the level of semi-finished materials, this is done via roll-cladding, for example, of copper and steel. In the maritime industry, fitting aluminum superstructures to steel hulls may be achieved by means of explosion welding. However, both solutions require an actual joining operation beyond shaping and thus violate at least some process-oriented hybrid material definitions. Co-extrusion does not, however, and has been demonstrated, for example, for combinations of aluminum and titanium[26] or aluminum and steel.[27] Examples of structures in which separate

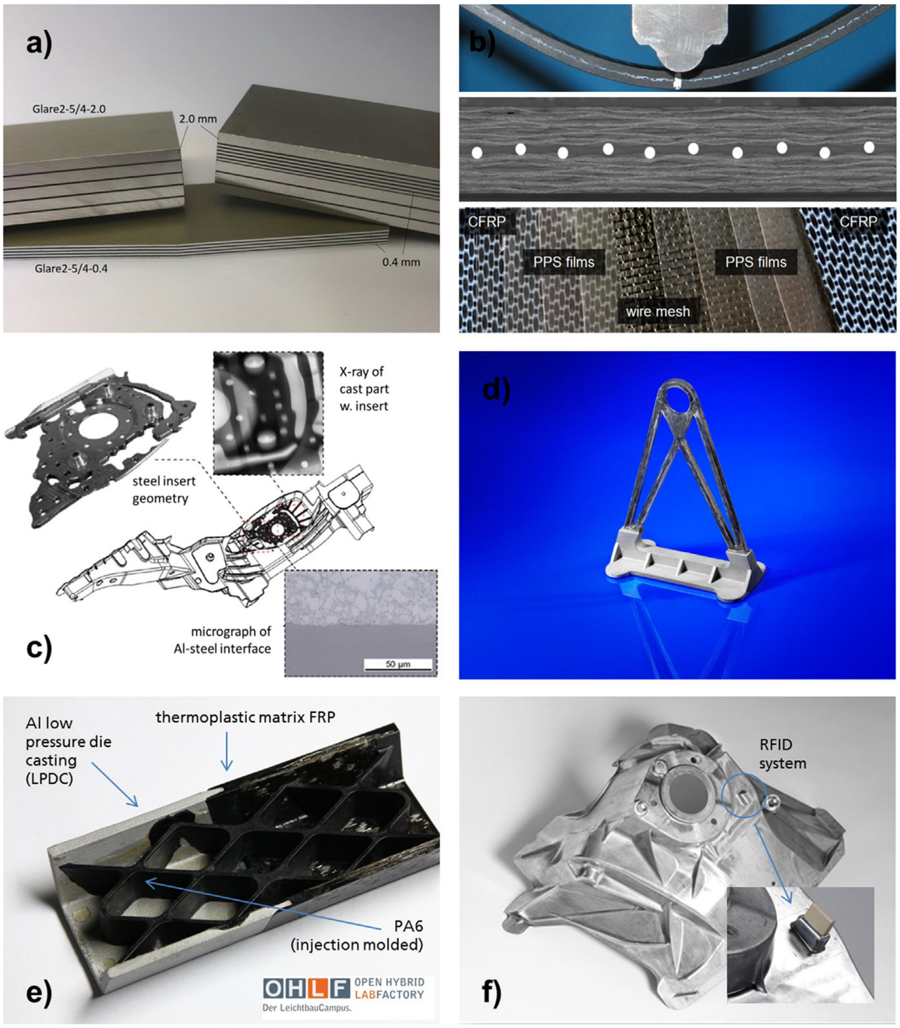

Figure 1. Examples of hybrid materials and structures: a) GLARE, a fiber-metal laminate (FML) of aluminum and glass-fiber reinforced composite layers of varying thickness and, in the case of the FRP layers, orientation (image courtesy of TU Delft), b) a laminated hybrid material incorporating carbon fiber reinforced composite, thermoplastic polymer and steel wire mesh layers facilitating forming operations (images courtesy of Leibniz IWT, top, cross section, bottom, materials combined), c) a high pressure die cast aluminum longitudinal carrier with integrated, topologically optimized steel insert (image courtesy of BMW), d) a hybrid structure consisting of high-pressure die cast (HPDC) aluminum alloy and carbon fiber reinforced composite (CFRP) joined together during casting (image courtesy of Fraunhofer IFAM), e) a hybrid structure consisting of aluminum casting, shaped thermoplastic matrix CFRP and injection molded thermoplastic stiffeners which at the same time support joining of the individual components (image courtesy of Fraunhofer IFAM/OHLF), f) a casting with integrated electronic component, that is, an RFID system, as example of a smart hybrid structure (image courtesy of Fraunhofer IFAM).

processes are employed to create the hybrid are shown in **Figure 2**, ranging from local strengthening using weight-optimized metallic inserts in FRP-based sandwich structures to increase the transferable loads of bolted joints[28] as in Figure 2a to the use of induction welding for joining FRP to metal structures (Figure 2b) and the realization of a hybrid titanium–aluminum seat rail via laser welding.

2.2.2. Applications

Aerospace: Easily the most prominent application of hybrid materials in the aerospace industry, and probably in all branches of the transport industry is the upper part of the Airbus A380s fuselage, and its empennage leading edges, which are made of GLARE: In this function, the material excels through its excellent fatigue and damage tolerance properties, as well as its impact resistance and tolerance characteristics. Its practical implementation was further facilitated by its treatment as metallic material, allowing qualification on material rather than structural level. The A380 application also echos the fact that GLARE has actually originated from an aerospace context, with first developments in the field of metal–metal laminates performed as early as the 1940ies by the Dutch company Fokker, later to be translated into metal-FRP variants with major contributions from the Faculty of Aerospace Engineering at Delft University of Technology. Even earlier claims are linked to the De Havilland Mosquito developed in the 1930ies featuring adhesively bonded components combining would and metal in its primary structure.[29]

Nowadays, GLARE and other FML-type materials find additional interest in the space industry, with ESA. Here, the focus is less on fatigue and more on impact characteristics where protection of structures in space is the main issue. The possibility of improving the performance of bolted joints in FRP through integration of metal layers has motivated study of local hybridization, for example, for launcher structures.

Beyond the primary structure, other areas of application for hybrid solutions reflected in the present overview include seat rails as depicted in Figure 2c, or cabin brackets, on which the demonstrator in Figure 1d is modeled.

Automotive: With an economic background which significantly differs from the aerospace industry in that the value of a kg of weight saved is far lower, the automotive industry is not in a position to directly take over materials and processes from the former. Nevertheless, examples like the use of carbon fiber reinforced composites, for example, in the BMW i3, which were originally limited to low production volume luxury sports cars, show that with adequate adaptation, a transfer is indeed possible. The BMW i8 in contrast underlines the fact that besides metal or even CFRP-dominated designs, wherever this is economically justified, realization of hybrid designs is among the preferred solution. This indicates that wherever technological and performance issues are the pivotal ones, multi-material approaches may prevail. Thus it may be assumed that if costs associated with hybrid materials and structures can be reduced, their market penetration will likewise increase – a line of thought which, as one possible strategy toward this aim, suggests the implementation of processes which eliminate additional process steps like joining operations. Compound casting is one example of a technology which is based on adopting this approach.

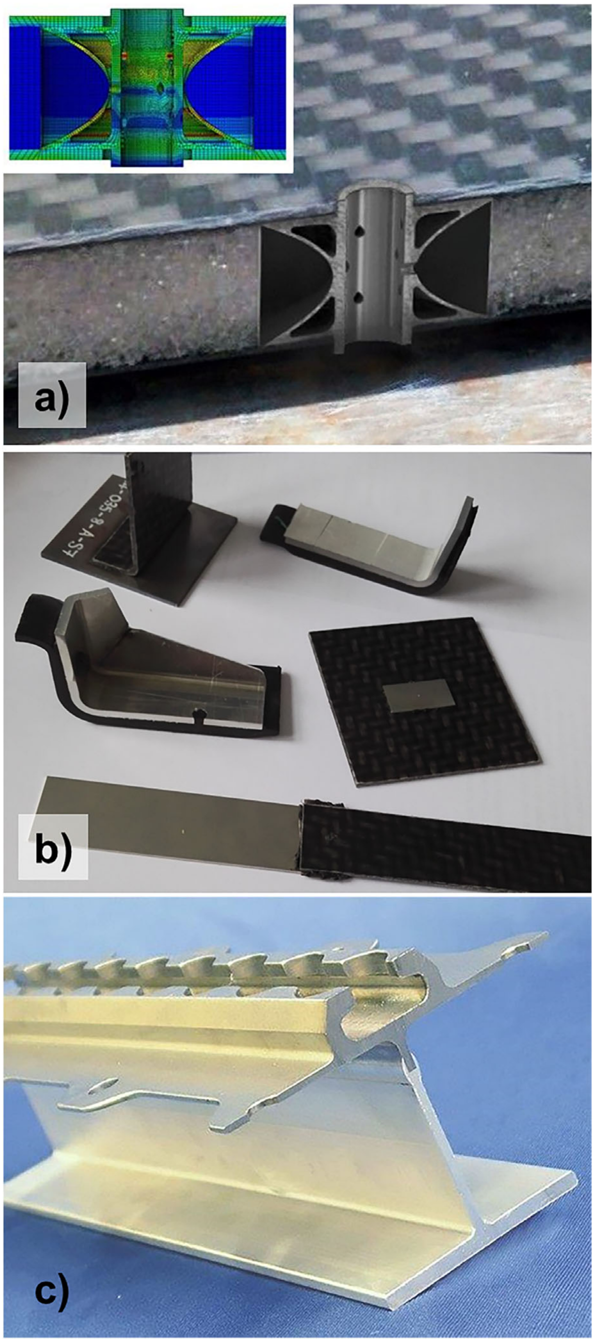

Figure 2. Examples of hybrid materials and structures based on separate bonding processes: a) An additively manufactured metallic insert in a sandwich panel with FRP skins for realizing high performance bolted joints (image courtesy of Leibniz IWT, Bremen), b) several examples of induction welded metal-FRP hybrid structures (image courtesy of IVW, Kaiserslautern), c) a commercial airliner seat rail with titanium upper and aluminum lower part joined by laser welding (image courtesy of Leibniz IWT, Bremen).

Renewed interest of automotive OEMs as well as their suppliers in hybrid solutions realized via compound casting processes is based on attempts at introducing large-area structural castings in general. As parts of the automotive body, such components have to be connected either to wrought aluminum or steel structures, and in some cases even to fiber-reinforced composites. A good example of such extended multi-material designs is the current 7 series BMW, the body of which comprises CFRP, aluminum and high strength steel elements, though currently not relying on compound casting processes for production. The attractiveness of introducing the latter would be based on the possibility of saving process steps. This example underlines the fact that besides pure metal or even CFRP-dominated designs, wherever this is economically justified, realization of hybrid designs is among the preferred solutions. This indicates that wherever technological and performance issues are the pivotal ones, multi-material approaches may prevail. Thus it may be assumed that if costs associated with hybrid materials and structures can be reduced, their market penetration will likewise increase – a line of thought which ultimately suggests focused development of processes which eliminate joining operations as additional steps. Compound casting is one instance of a technology which is based on adopting this approach.

Compared to the automotive and aerospace industry, in rail as well as maritime industry and marine engineering far less publications are available on hybrid materials and structures. While the rail industry may be said to resemble the aerospace industry in aspects like typical production volumes, weight reduction benefits – especially economic ones – are not comparable to the former. Similarly, in the maritime industry, cost of common materials typically prohibits a replacement by hybrid structures. There are niches, though, in which these general rules of the game may be bypassed – these include military or luxury crafts, or high speed trains for that matter, which could benefit both from impact and fatigue characteristics of, for example, FMLs.

3. Contributions to the EUROMAT Symposium

The papers which form the current Special Section cover, besides hybrid materials, the areas of polymer matrix composite materials, metal casting, and advanced experimental approaches for development of metallic materials.

In his contribution, René Alderliesten discusses hybrid materials for aerospace applications by switching the perspective from configuration-based prediction of properties of such multi-materials to reversed approaches toward the design of optimized combinations of metal and fiber reinforced composites based on known requirements and load cases. The paper starts with an overview of theories describing strength, fatigue and damage tolerance. In terms of materials, the focus is on fiber metal laminates.[30]

Hagenbeek et al. discuss the effects of a further functionalization of a hybrid material on long-term stability and properties: Based on their layerwise build-up, fiber metal laminates lend themselves easily to the integration of active components. In the present case, heating elements are integrated in aluminum–glass fiber type FMLs for aerospace applications to provide deicing capabilities. The effect of increased thermal cycling on mechanical properties caused by an introduction of such systems is studied experimentally and evaluated on the basis of changes of interlaminar shear strength.[31]

Rehra et al. investigate a hybrid material which essentially consists of a carbon fiber reinforced composite (CFRP) with thermoset matrix incorporating additional steel fibers, constituting a material designated accordingly as SCFRP. The study concentrates on deriving an analytical model capable of describing the failure behavior of the material under a load parallel to the fiber direction.[32]

Jenkins et al.'s study on the influence of reduced graphene oxide (rGO) as nanofiller to modify epoxy matrix characteristics in a CFRP can be seen as a bridge between conventional fiber reinforced composites on the one hand and hybrid materials and nanocomposites on the other. In it, bending and shear tests are performed at different rGO content levels which concentrate on the influence of temperatures between -10 and $+40\,°C$ on mechanical characteristics and failure modes.[33]

Hamid et al. scrutinize chemical modifications of the interfaces between reinforcing glass fibers and a thermoplastic matrix in glass fiber reinforced polymers (GFRP). As a second aspect, a characterization method capable of accurately determining interface properties is described and evaluated using actual experimental results using the physical test setup developed on the aforementioned materials with a variety of surface modifications in combination with numerical investigations allowing to assess the contribution of the interface to overall mechanical properties.[34]

Cramer et al. concentrate their work on the development of new metallic materials, with a focus both on compositional and processing influences on material performance. They present a new property evaluation methodology based on characterization of micro scale samples. As example 100Cr6 steel is chosen in this study, which paves the way for using high-throughput experimental methods in the design of materials.[35]

Merchan et al. report about a new variant of the low pressure die casting process applied to the production of aluminum components. Their modified process is designated low pressure squeeze casting (LPSC) and incorporates the exertion of pressure on the solidifying casting to improve, through supporting direct contact between part and mold, heat extraction from the casting, thus increasing solidification rates, and reduce porosity by keeping larger amounts of gases in solution and providing internal feeding effects. Among the results are reduced cycle times as well as increased strength, fatigue life and elongation at failure.[36]

4. Future Trends

4.1. So What Will the Future Bring?

Hybrid will certainly remain a major catchphrase, as it describes the use of each material in the place where its individual properties are best exploited and synergistic effects may be realized in the resulting multi-material, multi-component structure.

Beyond multi-material and hybrid structures, a strong growth is to be expected in Additive Manufacturing, with processes maturing, costs reduced, and dedicated simulation tools to better predict process outcome and part performance available. Here, the aerospace industry is currently taking the lead, but an uptake of the technology by the automotive industry is already happening now, with far less delay than in the aforementioned case of CFRP.

Evaluation and, eventually, establishment and commercialization, of advanced AM processes and approaches which take multi-material down to the actual material level, facilitating design of materials on a scale of tens of micrometers, or less, may further support this trend and ultimately pave the way for a new type of hybrid materials with much increased freedom for optimally configuring the partner materials' geometries according to their respective strengths. The prerequisite is the development of processes that transfer the general geometrical flexibility of the AM processes to independently locating several different materials within a single component. Currently, approaches toward this end are, for example, known from the binder jetting AM process, in which the binder can be used as carrier medium for transfer of either inert or reactive additives.[37]

Hybridization will more and more be extended to the field of smart structures and material-integrated intelligent systems,[25,38] addressing markets beyond the already deeply investigated aerospace or wind energy plant structural health monitoring and using AM as well as other manufacturing processes like metal casting (see Figure 1f) as vehicle.[1,23,24,39] A specific motivation for this latter point may be found in the trend toward autonomous driving. It is a fallacy to assume that this technology can solely rely on vision and inter-vehicle communication, not the least because coping with everyday traffic situations is not the only task a self-sufficient car has to tackle – beyond this, a human driver will employ more than vision to assess the overall state of his vehicle. For this, she has all her senses at her disposal. For an autonomous vehicle to provide equal levels of safety, a comparable array of sensorial capabilities is needed.[40]

5. Conclusion and Outlook

As the interest in lightweight design solutions will remain, so will the authors' EUROMAT involvement: The next edition of our symposium "Advanced Materials for Transport Applications" is already scheduled as symposium E1 of EUROMAT 2019 to be held at Stockholm from September 1st to 5th, 2019. Hybrid materials, structures and processes will certainly be an important part of this event, but beyond it, we offer an expanded stage for Additive Manufacturing topics: If related to applications in the transport sector, these can be submitted to symposium E1. If related specifically to exploiting unique AM capabilities in development and processing of advanced materials, be they metal-, polymer-, or ceramic-based, we invite our readers to submit their work to EUROMAT 2019 symposium C5, designated "Additive Manufacturing of Composites and Complex Materials IV". This symposium is the fourth in a series established at the MS&T conferences 2016, 2017, and 2018 and will also be covered in a Special Section of Advanced Engineering Materials due to be published after the event.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

aerospace industry, automotive industry, hybrid manufacturing processes, hybrid materials and structures, lightweight design, maritime industry, railway industry

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