IWM – IAPK Colloquium 2018: Strength of Additive-Manufactured Components

The invitation to the second public colloquium of IWM/IAPK/DE (Institute of Ceramics Process and Application Engineering/Institute of Ceramics Process and Application Engineering at RWTH University of Aachen) at the Technology Centre at Europaplatz in Aachen/DE was taken up by 85 attendees. Eight external speakers from industry and research, as well as three speakers from IWM and IAPK had prepared papers on topics centring on additive manufacturing.

Fig. 1
Prof. Dr-Ing. Christoph Broeckmann

Introduction

In his welcome address, the host Prof. Dr-Ing. Christoph Broeckmann (Fig. 1), Head of IWM and Director of the IAPK, made clear how important it is to be able to satisfactorily answer questions regarding the reproducible strength and reliability of additive-manufactured components. He continued: "Optimum embedding of the Additive Manufacturing step in the process chain overall and questions regarding appropriate quality assurance are of great importance for the transfer of the process into production. One goal is consistent assurance of mechanical properties that are on a par with or even superior to those of conventionally manufactured components. Research is concentrating on properties that describe complex load conditions (vibration resistance, creep resistance, fracture toughness). Another goal is the search for validated calculation methods and design specifications on the basis of which additive-manufactured components capable of withstanding high mechanical loads can be designed."

Papers

In his introductory talk, Prof. Dr-Ing. J. H. Schleifenbaum (DAP/RWTH Aachen – Fraunhofer ILT/DE) gave an overview on "Current and Future Developments in Additive Manufacturing (AM)". His observations referred essentially to the processing of metal powders. Here already 35 % of components are produced industrially – the rest is prototyping and research. A particular challenge for additive manufacturing will be to realise the concepts of Industry 4.0 in production. AM is certainly at the heart of evolution in industrial manufacturing, but its integration in the process chain overall must be resolved.
Research not only determines the mechanical properties of AM components, but investigates the adjustment of microstructures and AM design in respect of the component properties. The vision is "digital materials" in which material properties and lattice structures are coordinated with each other.
Prof. Dr-Ing. Mirko Schaper (LWK Paderborn/DE) spoke on the "Influence of the Microstructure on the Fatigue Behaviour of Additive-Manufactured SLM Components". Additive-manufactured components differ from conventionally manufactured components not only because of the greater geometric freedom in shaping, but above all with regard to the process-related formation of other microstructures. Besides the (minimal) porosity of the components and their rough surface, the essential differences can be found on microstructural level. With the multiple fast solidification sequences and the cyclic heating during the construction of higher-lying layers, for practically all alloys, microstructures are formed that differ significantly from those of other manufacturing processes. While these structures often lead to higher strengths when exposed to quasi-static stresses, they generally have a negative influence on the fatigue properties of additive-manufactured components. Referencing the example of powder-bed-based AM processes (Selective Laser Melting, SLM®), this paper showed how it is possible to influence the microstructural properties of samples with the adjustment of the process

parameters, heat treatment or hot isostatic pressing so that at least the performance of conventionally manufactured components can be matched. The typical interaction between process, microstructure and the fatigue properties was characterized for the alloys 316L, IN718, TiAl6V4 and AA7075 on the level of dislocation, precipitation and grain structure.

Dr-Ing. Anke Kaletsch (IAPK) explained the "Influence of Various Post-Treatment Routes on the Mechanical Properties of a Generatively Manufactured Hot-Working Steel" (Fig. 2). In the past few years, laser-based AM in the L-PBF process (Laser – Powder-Bed-Fusion) has registered a steady increase in research activities. Steels that undergo martensitic transformation during cooling are very difficult to manufacture crack-free in the very fast cooling conditions of the L-PBF process. Martensitic steels manufactured with L-PBF often contain a large number of microcracks. Besides these, as a result of the process, pores, joint defects and other defects can exist in the microstructure. This leads to a reduction in strength and especially in fatigue strength. One possibility to minimise the defects in the microstructure of additive-manufactured materials and components is hot isostatic pressing in the HIP-process. In HIP, very high pressures are applied, which, depending on the material, can reach up to 2000 bar, simultaneously with temperatures not far under the respective melting temperature. With this process, pores, joining defects and cracks can be permanently closed. One exception are pores that are filled with argon as argon

Fig. 2
Dr-Ing. Anke Kaletsch

is not soluble in the crystal lattice of metallic materials. If argon pores are compacted in the HIP process, on repeated heat treatment of the material, they can grow. With the L-PBF process, samples of hot-working steel H13 (X40CrMoV5-1) can be manufactured with very high relative densities up to around 99,8 %. In the "as-built" state, the material showed, however, besides low residual porosity a large number of microcracks. In addition came a relatively high residual austenite content up to 17 %. After tempering, no residual austenite could be detected. As a result, the hardness could be increased from 592 ± 11 HV10 to 628 ± 11 HV10. However, the measured fatigue strength of the tempered steel was worse than in the "as-built" state. As the reason for this, it can be assumed that the increase of the hardness is accompanied by a decrease in the crack tolerance. As a result, the microcracks in the tempered state lower the fatigue strength to a greater extent than in the less hard "as-built" state. Microstructural analyses could prove that the microcracks from the L-PBF process remained unchanged in the material after heat treatment. If hot isostatic pressing of the L-PBF samples was performed upstream of the tempering process, the fatigue strength could be increased notably.

The "Vibration Resistance of Generatively Produced Hot Isostatically Post-Treated Steel" was discussed by Dr-Ing. Markus Schneider and Dennis Wawocny (GKN Sinter Metals/DE). A frequently used material for generative production of components is 316L. On account of its good weldability and the low carbon content, this material has become established in additive manufacturing. The use of a new material necessitates extensive tests. Moreover, it is important to validate robust process variants and possible post-treatments to lend the component high technical value in use, If the material is solution-annealed and quenched after generative production or hot isostatic pressing, embrittling precipitation can be largely avoided. A faster cooling after or during hot isostatic pressing would be desirable. Providing the permissible application range is observed (for instance, below 400 °C), the material can be used to advantage. The combination of high static

Fig. 3
Auditorium

ductility, low medium-voltage sensitivity (perfect medium-voltage insensitivity), low notch sensitivity, acceptable strength under reversed bending stresses, low scattering and high corrosion resistance can then be expediently used for additive manufacturing.

J. Kunz (IAPK) assessed the "Properties of L-PBF-Manufactured Austenitic-Ferritic Stainless Steels". In this study, the properties of L-PBF-manufactured austenitic-ferritic stainless steels were investigated. As austenitic steel, X2CrNiMo17-12-2 (1.4404), and as austenitic-ferritic steel, X2CrNiMoN 22-5-3 (1.4462) were used. At the focus of the studies are the formed microstructure and the mechanical properties. Mechanical characterisation is based on tensile strength and the strength on cyclic loading.

Besides the determined profile of the steels, properties achieved with different post-treatment strategies were shown. Steel X2CrNiMo17-12-2 is hot isostatically pressed (HIP) after the L-PBF process. In the HIP process, pressure and temperature have a parallel effect on the sample. The effects on the additive-manufactured material are analysed and compared with the "as-built" state. The "as-built" properties of Steel X2CrNiMoN 22-5-3 were compared with two post-treatment routes: solution annealing and the combination of HIP, and a downstream solution annealing. Solution annealing creates the typical α/γ microstructure.

J. Zhang (IWT Bremen/DE) reported on "Initial Findings of Fatigue Tests on SLM-Generated Samples". Additive-manufactured components can exhibit a higher pore content and anisotropic material properties or residual stresses. Accordingly, in comparison with conventionally manufactured components, they exhibit unfavourable properties. For structural components, however, mechanical behaviour under static and dynamic load is highly important. It is therefore important to acquire an in-depth understanding of the mechanical behaviour of additive-manufactured components. With the SLM process, samples of austenitic steels and tool steels were additive-manufactured, which were studied in comparison with conventionally manufactured steels.

Dr-Ing. D. Greitemeier (MTU/DE) reported on the "Influence of Additive Manufacturing on the Lifetime of Engine Components. The precursor material (gas-atomized powders), SLM process and the post-treatment have been identified as the main influencing factors. Problems are caused not only by porosities on the inside, but by non-melted particles, impurities and only partially melted particles on the surface and surface-near porosities. A simulation chain to estimate the material properties was developed and finishing methods (grinding and blasting of the surfaces) included in the assessment.

F. Palm (Airbus/DE) spoke on the "HIP of Al-Materials from the Laser Powder Bed Melting Process – Observations, Limitations and New Possibilities". For cost efficiency, laser powder bed melting of Al-materials is generally conducted in a melting process regime in which the so-called keyhole welding mode can lead to increase microstructural imperfections. Pores or solidification cavities always reduce the loadable material cross-section, their often unround shape significantly reduces fatigue strength.

For strength-driven applications, such material grades would be rejected as inacceptable for components. Microstructural improvements (repair) appear possible only by means of HIP. However, its effectiveness for Al materials is often questioned as the existence of inherent oxidic cover layers and the hypothesis that gases from the process environment enclosed in pores of additive-manufactured materials generally prevent closing or welding. The speaker's own studies on AlMgSc and AlSi(Mg) alloys, however, prove the positive effect of hipping for laser powder bed melted material. As gas-assisted HIP-installations require a very long processing time, and in their technical design as "multi-use systems" (mirrored on a use for Al materials) cover an "oversized" temperature window, the HIP process often appears too expensive for series manufacture. For this reason, in the view of the speaker, especially for Al alloys from the laser powder bed, new recompaction concepts with considerable ratio potentials are required.

Chr. Broeckmann (IWM) discussed "Additive-Manufactured Lattice Structures: Understanding Failure – Utilising Potential". Modern generative manufacturing methods allow the manufacture of delicate lattice structures with new and promising potential especially for lightweight engineering. Instead of being made of dense, conventional materials, power-transmitting components are made of lattice structures, the density and mechanical properties of which are adjusted to withstand the local stresses. To perform reliable design calculations with such structures in the design process, knowledge of deformation, damage and fracture of lattice structures is necessary. Desirable for the calculation is a treatment of lattice structures similar to a high-porosity material. In the macroscopic analysis, it is necessary to be able to work with homogenized material properties without the microstructure of the lattice having to be explicitly reproduced in the component design process. The aim of the presented study was to contribute to this. Besides the experimental studies, numerical simulation calculations were performed with the goal of developing effective material properties to describe components built of lattice structures.

The numerical description of the lattice structure describes well the empirically measured stiffness, and the equivalence of explicit lattice modelling and simulation on the basis of effective properties can be successfully verified.

R. Gaignon (3DCeram Sinto/FR) reported on "New Applications of Hybrid Multicomponent Materials and Smart Design". He explained that while AM components can be manufactured without tools on the basis of digital data, enabling a short time-to-market, they are generally more expensive than components manufactured conventionally.

That calls for a rethink because AM components cannot sensibly replace conventionally manufactured components in economic terms. AM is suitable for applications that cannot be realised with conventionally produced components or only with such components after complex finishing. With AM, new possibilities are opened up to functionalize components. In the meantime, for the 3D-printing of ceramic components, it is possible to offer an entire manufacturing line that operates fully automatically and flexibly. It is interesting that in hybrid machines it is possible to process more than one material at the same time. The machines are available up to a useful area of 600 mm × 600 mm for the build-up of components.

It is, however, necessary that we do not only examine the manufacturing process alone. As work is based on digital data, completely new approaches are possible in the supply chain. The exchange of data between market partners is easy. Accordingly, new business models can be created.

Dr-Ing. K. Sauerzapfe (ALUMINA SYSTEMS/DE) concluded the papers session by talking about "3D-Printed Ceramic Components for Industrial Use". To enable better understanding of the difficulties associated with the market introduction of ceramic components, a brief overview was given of those component properties that justify manufacturing by means of 3D-printing. For economically successful use, certain requirements must be met in respect of component size, component precision and component complexity.

It is generally enough if one of the required properties (usually component size or component precision) cannot be directly achieved by means of 3D-printing for manufacturability to be technically no longer possible or for a conventional manufacturing process to make more sense in economic terms. With reference to the example of a small-series part, the cost problem was shown in competition with ceramic injection moulding. Examples of projects realised in the LCM process (milli extraction column, milli-siphon-reactor, test set-up, gas inlet ring), in which 3D printed ceramic components were used in different ways showed what strengths ceramic 3D-printing has when the correct application is chosen. Finally, the process of Laser-Induced Slip-Casting (LISC) developed by BAM, Germany's Institute of Material Research and Testing, was presented, which in future is to be developed to market maturity by ALUMINA SYSTEMS.