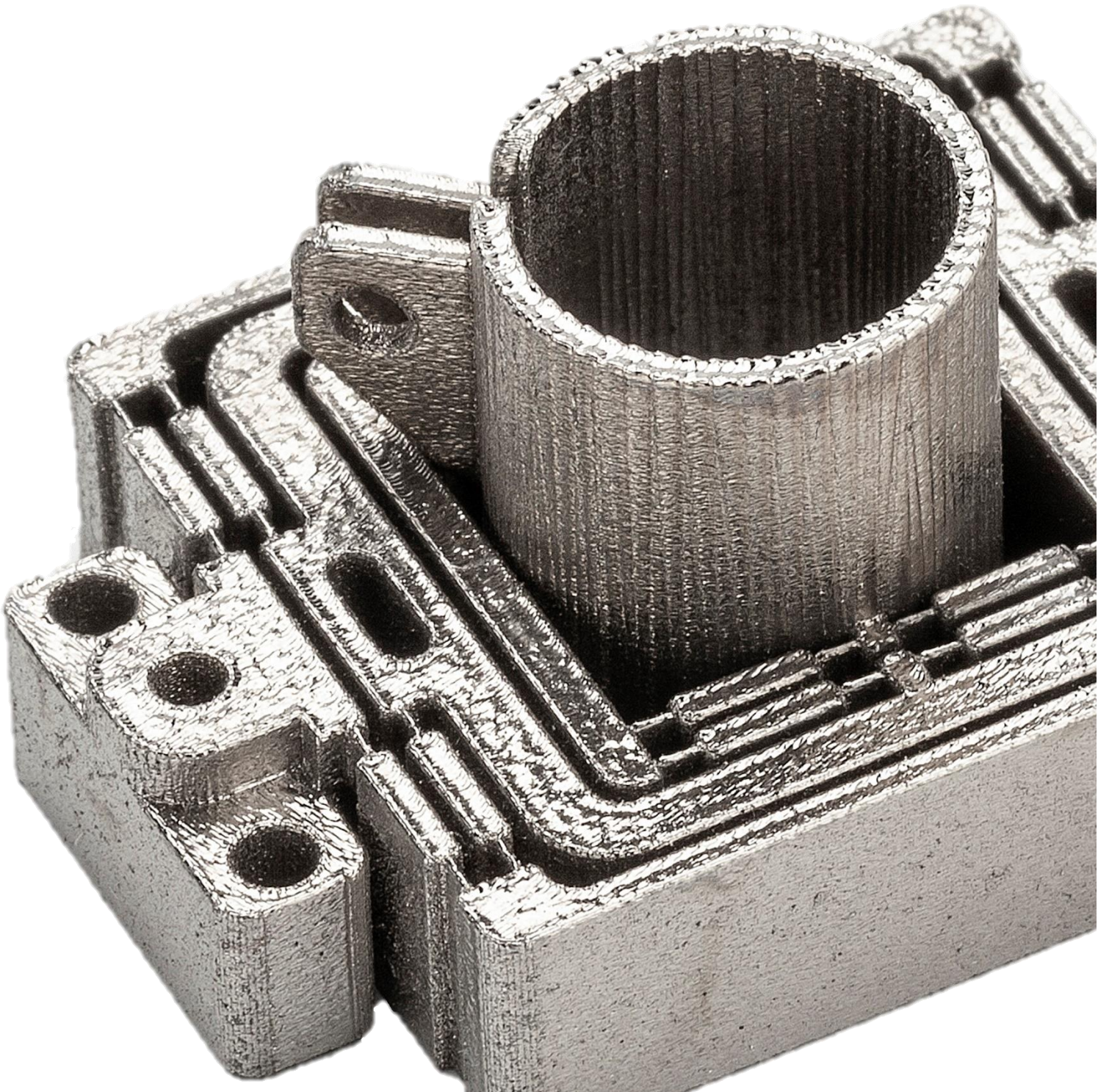


Case Study

3D PRINTED FLEXURES AND COMPLIANT SYSTEMS MADE OF AMORPHOUS ALLOYS

OVERCOMING LIMITS WITH A RESISTANT MATERIAL
USING AN INDUSTRIAL EXAMPLE



ABOUT TRUMPF

TRUMPF



TRUMPF is a high-tech company offering manufacturing solutions in the fields of machine tools and laser technology. The Company drives digital connectivity in the manufacturing through consulting, platform products and software. TRUMPF is a technology and market leader in highly versatile machine tools for sheet metal processing and in the field of industrial lasers. In 2020/21, the company employed some 14,800 people and generated sales of about 3.5 billion euros. With over 80 subsidiaries, the TRUMPF Group is represented in nearly every European country as well as in North America, South America and Asia. The company has production facilities in Germany, France, the United Kingdom, Italy, Austria, Switzerland, Poland, the Czech Republic, the United States, Mexico and China.

From prototyping to industrial series production. As a pioneer in additive technologies and laser specialist since 1979, TRUMPF offer the right technology for every application requirement: Laser Metal Fusion (or Laser Powder Bed Fusion) or Laser Metal Deposition. Benefit from complete industrial solutions with intelligent monitoring and smart services from a leading high-tech mechanical engineering company worldwide.

CUSTOMER SPECIFIC APPLICATION CHALLENGES

The conventional design of joints and hinges is conceivably simple, since only geometric and kinematic considerations of inherently rigid bodies and their relative motion are relevant. Loads, stresses and strain relationships are only considered in the parametric dimensioning of the overall design. Nevertheless, these designs are always associated with suboptimal frictional play and wear, multi-part construction and corresponding assembly efforts, as well as the usually very costly effort of subtractive CNC fine machining.

In TRUMPF's challenging case, the design of a solid-state hinge, which is more complex, eliminates all of the aforementioned suboptimal characteristics. The solid-state hinge, 3D-printed in this case, is screwed onto a plane of an optic of a laser guide and connected to the thread of a motor spindle with a clamp. If the spindle now moves, the solid-state joint moves and the connected plane (i.e. the optic) moves with it. A closer look reveals that the webs of the solid-state hinge are spring-loaded and absorb the imbalances and movements of the spindle, resulting in smooth and even motor running and travel. Due to the high demands on accuracy and reproducibility, conventional hinge systems are reaching their limits. TRUMPF has therefore already ventured the step toward compliant systems (solid-state hinges) and tested the first components with a 17-4 PH material. But here, too, the limited performance of the base material led to long alignment times, high motor currents and an associated high load on the drive. Due to the high energy and good thermal conductivity of the metallic material, the components heated up strongly and an accurate, controllable and synchronized motion sequence could not be guaranteed.

In this case study, the potential of flexible and compliant systems in mechanical engineering and their technological advantage through the use of amorphous metals in 3D printing are examined in more detail using the machine element of a solid-state hinge itself and the success story of the TRUMPF company.



CHARACTERIZATION OF FLEXURE ELEMENTS

A conventional swivel joint is the standard solution for a load-bearing rotational connection. It is one of the most widespread construction elements and is ubiquitous, whether as hinges, switches, in automatic machines and systems or as folding mechanisms. However, the conventional design of swivel joints is suboptimal, as previously described. In addition to the aforementioned losses due to friction, wear and assembly cycles, there is the lubricant requirement due to rolling and sliding contact principles that allow contamination. An efficient alternative is offered by compliant connections, which are not based on rolling or sliding between rigid bodies, but on the controlled, reversible deformation of elastic areas and cross sections. This results in neither play nor friction. One-piece, assembly-free designs, which are maintenance-free and operate silently without abrasion and thus without particle release, are lubrication-free in operation and enable more precise movements. They are also particularly lightweight and easy to clean, which is especially important in the food and pharmaceutical industries.

As shown in figure 1, the basic factors affecting the elastic behavior of idealized solid-state joints are the effects of stiffness in relation to geometry, material, loading condition, and environment. The idealized solid-state joint shown here has a semicircular, conical cross-section, while the most common variants of solid-state joints in compliant systems are based on the principle of a leaf spring and are corner-shaped.

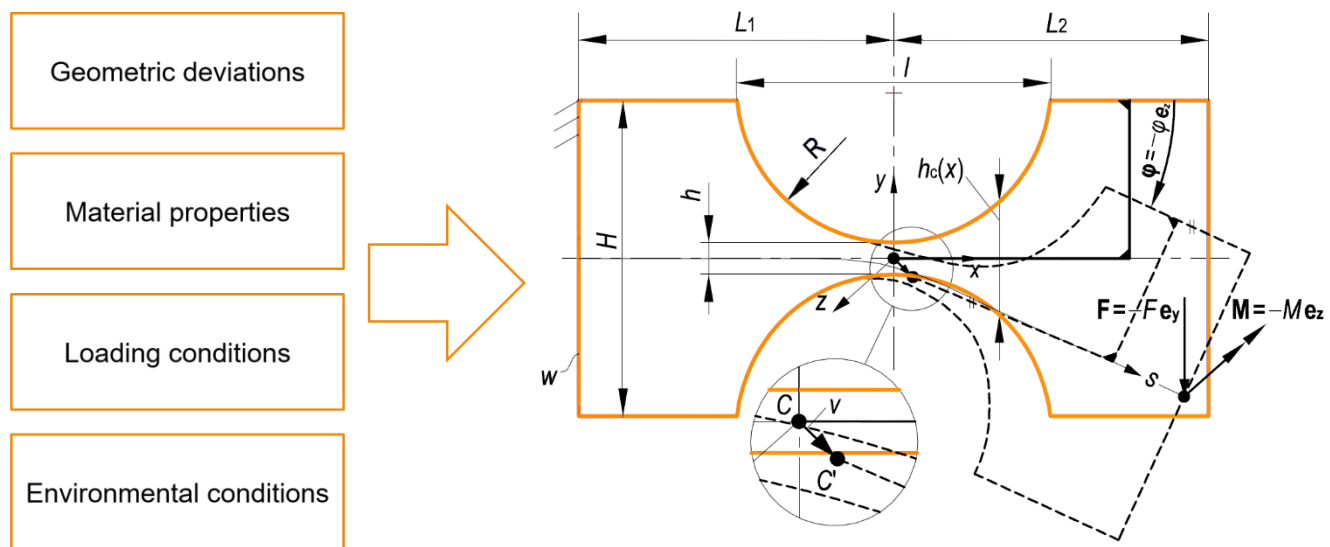


Figure 1: Idealized unit of a solid-state hinge and its influencing factors

Designing compliant systems has many advantages but is fraught with implementation biases due to the more complex approach. The core problem lies in the misjudgment of the load-bearing capacity of solid-state hinges, which are usually used where mechanical loads are not the primary concern, such as in precision or microsystems or as foil joints in closures of plastic containers and bottles. Thanks to new innovative materials, optimized geometry and more comparable size variants, solid-state hinges can compete with conventional hinge assemblies in terms of load capacity. They can even be made more slim and streamlined, which makes them ideal for lightweight construction. Furthermore, the ongoing development of the solid-state hinges led to completely flexible and compliant mechanisms, in which rigid links and joints merge into a single unit. In this way, complex assemblies or even entire mechanisms can be designed with a material bond. Mechanisms with dimensions of 100-500µm offer the greatest potential

for cost-effective, monolithic manufacturing on a generative or additive basis. Depending on the size, injection molding and 3D printing are ideal for this, eclipsing milling, laser cutting and other subtractive value chains.

One example of a completely monolithic system is material-assembled solid-state hinge mechanism. Here, too, the advantage is obvious. With classic joints, load transmission takes place via linear forces (plain, roller and needle bearings) or via point forces (ball bearings). The carrier material is not optimally stressed in the process. With solid-state hinge mechanisms, the material bond is not interrupted and the load is always transmitted via a defined cross-section; the design is even slimmer and thus lighter. Due to their lightweight potential, compliant systems are the key technology for reliable applications in aerospace and robotics.

CHALLENGES OF COMPLIANT DESIGNS

Compliant designs, as mentioned earlier, are much more complex than conventional joint and hinge systems. In conventional hinges, it is the geometry of the components in the assembly rather than the material that determines the kinematic relationships. The situation is different with solid-state hinges, whose permissible angle of rotation depends more on the chosen material than on the overall geometry of the assembly. In contrast to conventional hinges, the load-bearing capacity and service life of solid-state hinges are also related to the permissible swivel angle. If, for example, only moderate swivel capability is required, the hinge can be designed to be firmer or lighter, which can be controlled via the geometry based on the parameters of the material. However, this requires a holistic view of the entire mechanical system, but at the same time offers design and optimization possibilities that do not arise at all in conventional systems at this point and set limits. The design of a conventional hinge has approximately the same dimensions with the same load capacity, regardless of whether the joint is built for 5 or 50° pivoting.

Due to the complex deformation, the deformation behavior of compliant hinges cannot usually be calculated with linear models. For special materials such as highly elastic alloys, the consideration also becomes more complex at the material level, since the deformation mechanisms of crystalline materials are not always trivial due to phase transformations.

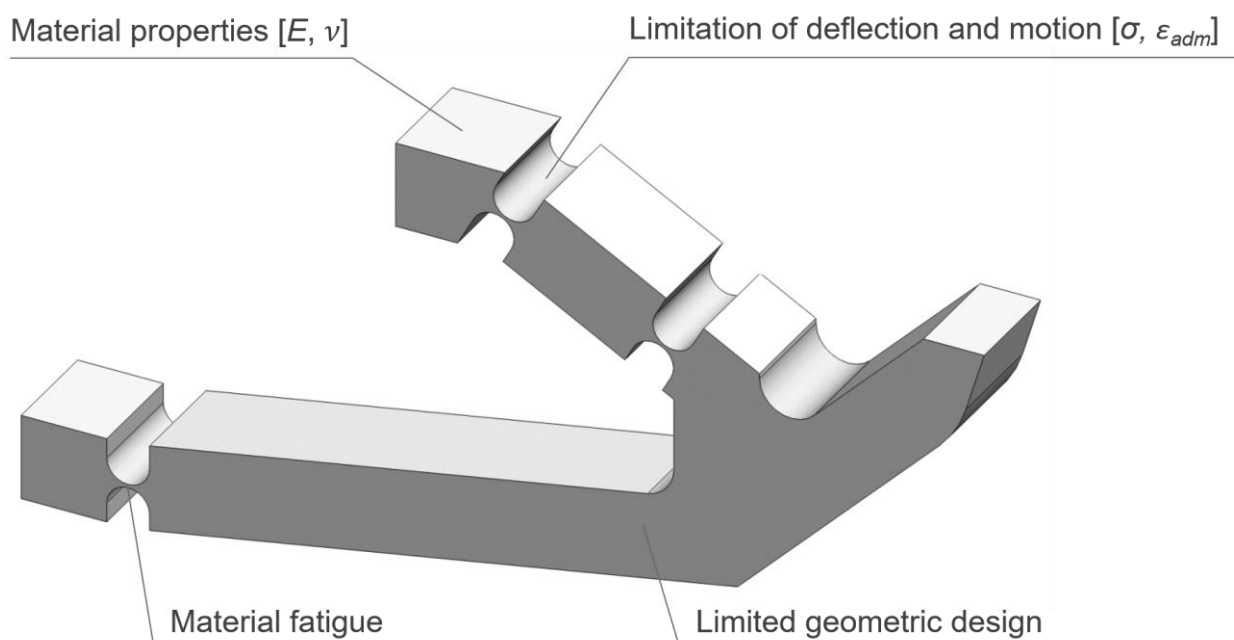


Figure 2: Factors of influence in the design of compliant systems

Due to the special geometry of the compounds, multi-dimensional stress states increasingly occur in the material, which further complicate an accurate prediction of the phase transformation and thus the macroscopic behavior. In addition, the material is too soft in larger monolithic systems. Due to the smallest possible ratio of maximum stress to deflection, only limited geometric shapes are possible. Material fatigue occurs either due to high fatigue stresses in bending or due to fatigue vibrations.

Overall, the limitation of deflections and movements is due to the strength of the bending beams. The different fatigue strengths of the materials do not lead to a sufficient realization of flexural hinges. The energy storage and possible oscillations of the stored elastic energy led to the fact that the energy is not completely transferred and the storage remains in the mechanism. Things get complex when combining the systems in non-linear equations, because the movement behavior of the mechanism is influenced by the displacement of the hinge rotation axis, which does not move trivially.

With these challenges of material properties, different fatigue strengths and limitations in deflection and geometric design, the stress field of conventional materials can be bridged in compliant systems. And beyond that, there are other as yet unsolved challenges in current applications of compliant mechanisms with conventional materials:



**Long alignment times in
precise positioning tasks**



**Thermal heating of
components**



**High maximum
motor currents**



Synchronization behavior



High load on the drive



**Accuracy and
controllability**

Figure 3: Conventional joint design with problem statements

SOLUTION: AMLOY MATERIAL FOR FLEXURE ELEMENTS

It has already become clear that the approach of using solid-state hinges is also associated with material hurdles. Although flexural elements can already overcome the problems of classic hinge designs, the properties of the materials that can be considered for compliant designs pose the described challenges for the designer. In this environment, amorphous metals are able to take on the complex requirement profile and, thanks to their versatile property portfolio, represent an ideal solution for the design of compliant systems and elementary solid-state hinges. Due to their high strength (even under fatigue) and high elasticity, amorphous alloys offer the advantage of high load-bearing capacity under a high number of cycles. The elastic behavior and the comparatively small modulus of elasticity lead to very good control of the cross-sectional area and thus also to a better design of the solid-state hinge, as the deflections can be controlled more precisely in relation to the force. Viable and cost-effective production processes in the field of selective laser melting enable replicable production of series components.

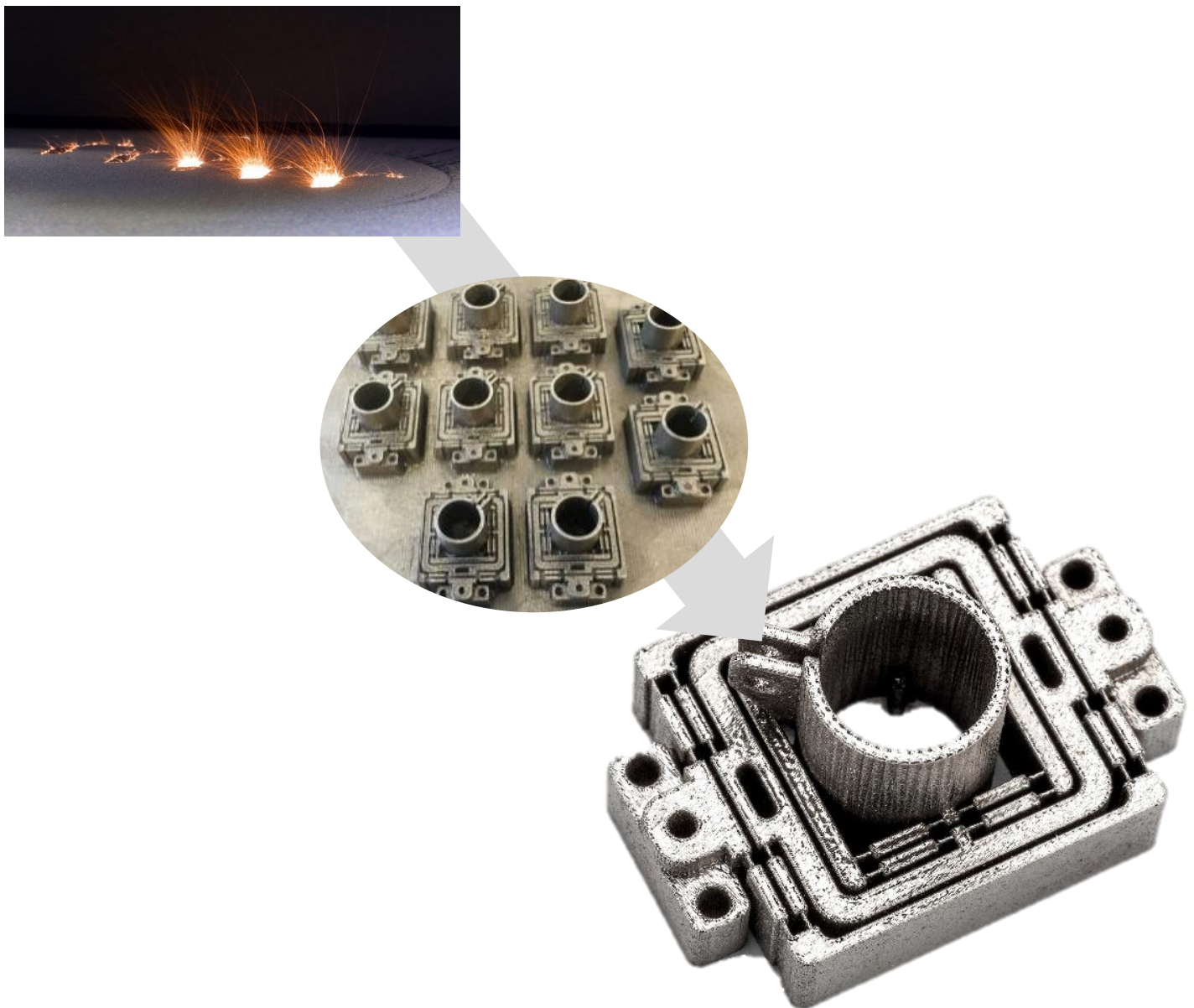


Figure 4: Realization of the ideal solid-state hinge by combining additive manufacturing with the innovative use of amorphous metals

These findings and advantages have ultimately led to the successful introduction of amorphous metals into TRUMPF's solid-state hinge application in the sensitive optics movement. Since the material class was completely new for this application at TRUMPF, a long development time was feared. This hurdle was also overcome and in a very short time not only the ideal printing parameter was achieved but also an improvement in the design dimensions with regard to the web width of the hinge elements in the flexible overall system. All in all, the change of material for the solid-state hinge at TRUMPF overcame all the original challenges in the final application:

- ☑ The maximum motor currents have been reduced and energy is saved as a result
- ☑ Improved synchronization behavior in the critical direction of movement was achieved
- ☑ Time for the previously necessary alignment process per motor has been eliminated
- ☑ Reduction of the motor current in the critical direction of movement was achieved
- ☑ The load on the drive has been reduced due to the reduced motor current consumption
- ☑ Thermal heating of the components has been reduced
- ☑ Improved positioning accuracy and controllability was achieved

” The material expands the classic choice of materials with a wide range of properties and enables applications that were previously not feasible.

– Stefan Dörr, Developer of the solid-state hinge and project manager at TRUMPF

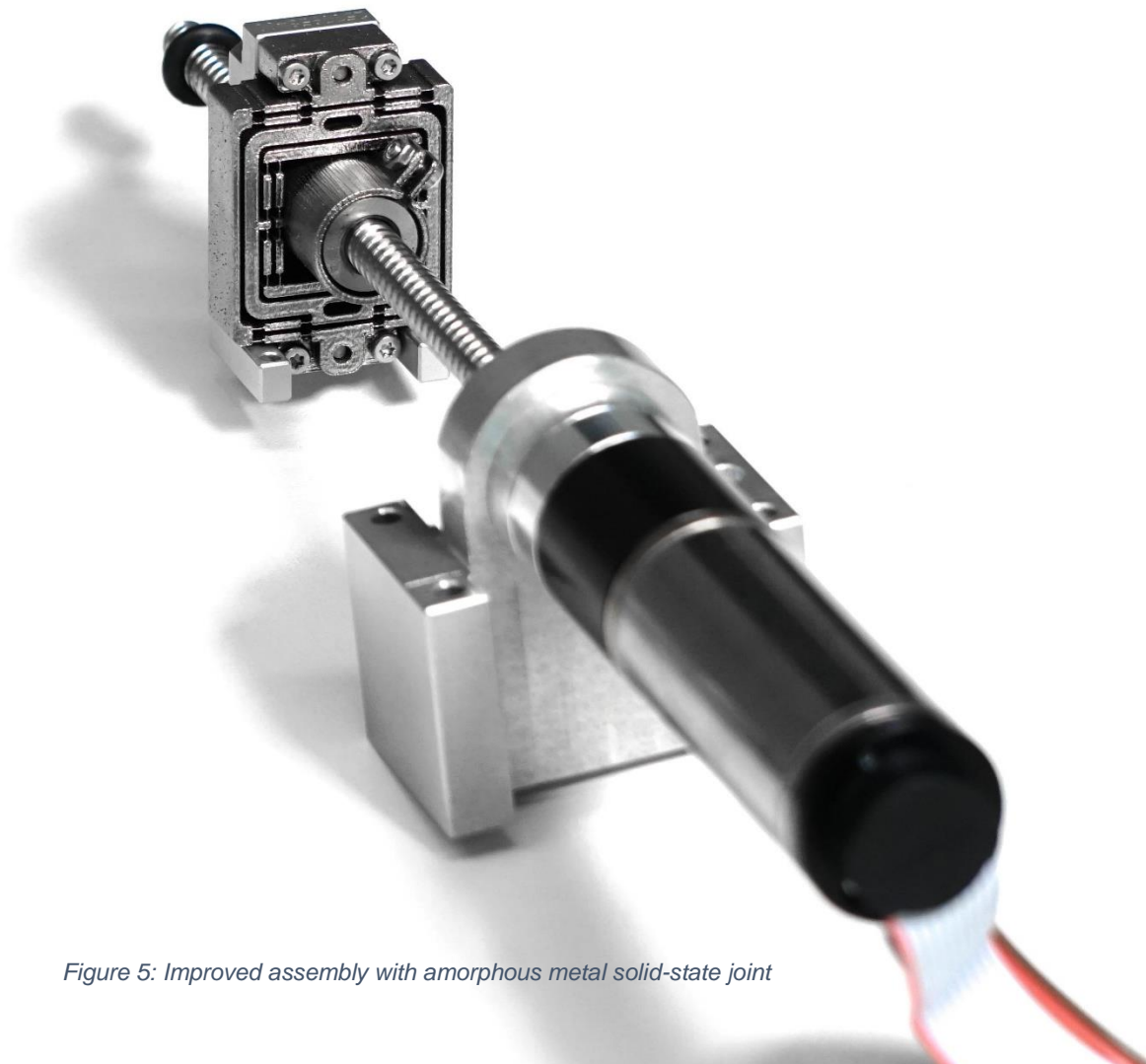


Figure 5: Improved assembly with amorphous metal solid-state joint

MATERIAL PERFORMANCE ANALYSIS

With suitable process parameters and laser strategies, amorphous components can be manufactured with relative densities $> 99.9\%$. Due to the presence of residual porosity, the mechanical properties of cast specimens are usually still undercut, but printed specimens already exhibit impressively high strengths and hardnesses without the components having to undergo subsequent heat treatment. While strengths of 1500 ± 150 MPa are measured in the tensile test, the printed material excels in the flexural test with values of over 2000 MPa. With a Young's modulus of nearly under 90GPa, the linear elastic behavior with almost 2% elastic deformation without post-processing is almost twice as high as that of post-processed crystalline materials.

Figure 6 shows the resulting performance differences in the component of a printed amorphous and printed steel structure. It becomes clear that the basic physical and resulting mechanical properties in near-net-shape production not only offer process advantages, but also enable applications that have previously reached their physical limits.

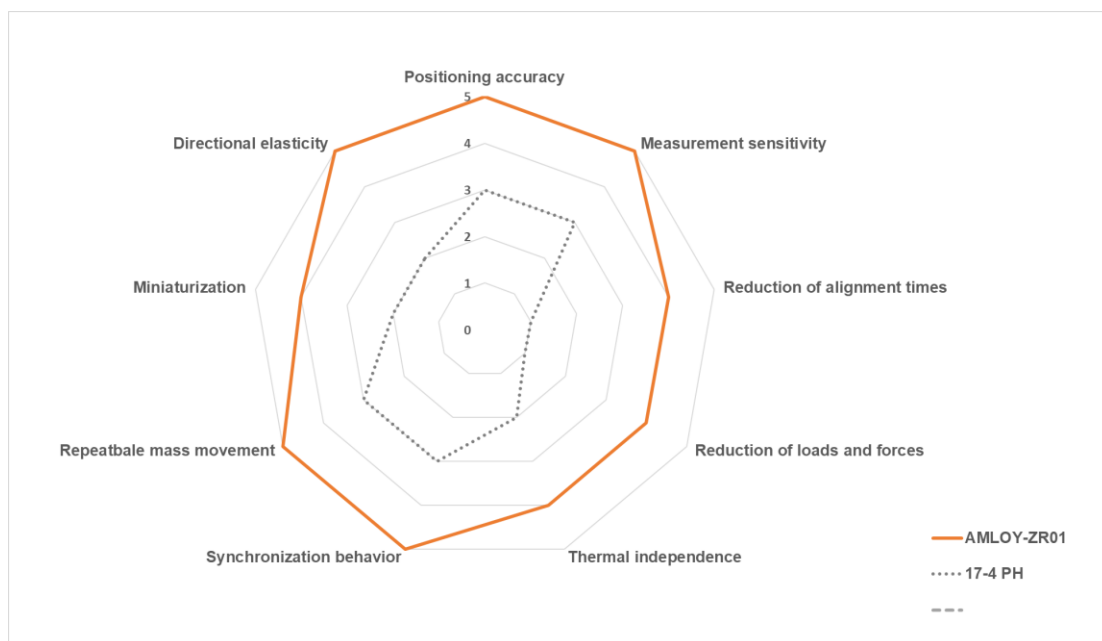


Figure 6: Performance comparison of material and component investigations

COMPARISON OF MATERIALS FOR FLEXURES

If we take a general look at materials for flexible systems and solid-state joints, the connection between the mechanical values outlined above and the performance of the machine element becomes clear. The combination of a high mechanical strength with a low elastic modulus leads to a high elasticity and consequently to a reproducible deflection capability of the tapered cross sections. This is clearly illustrated by the following example of a modeled solid-state joint with the basic element of a leaf spring. A case-hardened steel (15NiCr13), a stainless martensitic steel (17-4 PH) and the amorphous metal alloy AMLOY-

ZR01 are used for comparison. The geometric dimensions and the loading condition are identical in the test setup.

Material	Hinge contour	Tensile yield strength [GPa]	Young's modulus [GPa]	Elastic admissible strain [ϵ_{adm}]
15NiCr13	Corner filleted	0,6	210	0,29
17-4 PH	Corner filleted	1,1	180	0,61
AMLOY-ZR01	Corner filleted	1,5	87	1,72

Table 1: Comparison of the key material figures for flexures

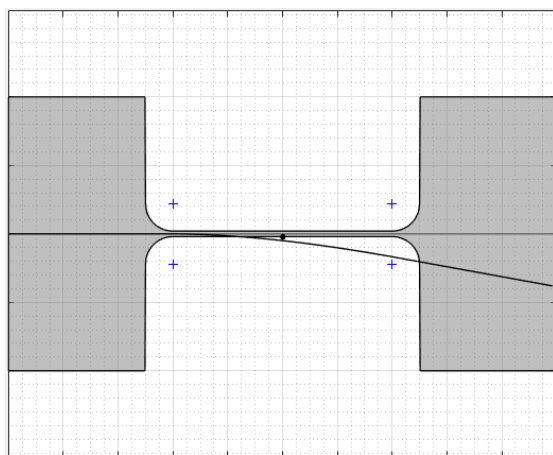


Figure 6: Geometry plot and strain distribution plot (15NiCr13: 0,01 distance until ϵ_{adm})

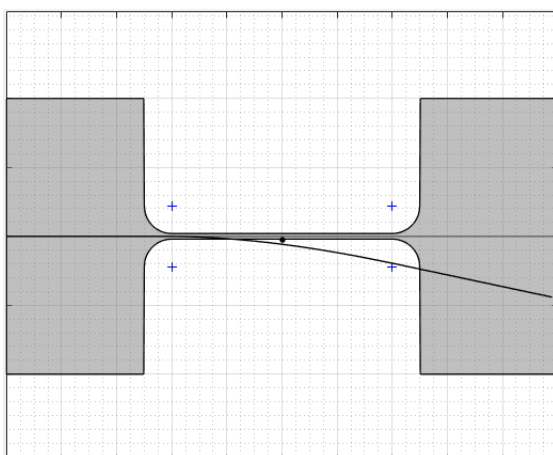


Figure 7: Geometry plot and strain distribution plot (17-4 PH: 0,22 distance until ϵ_{adm})

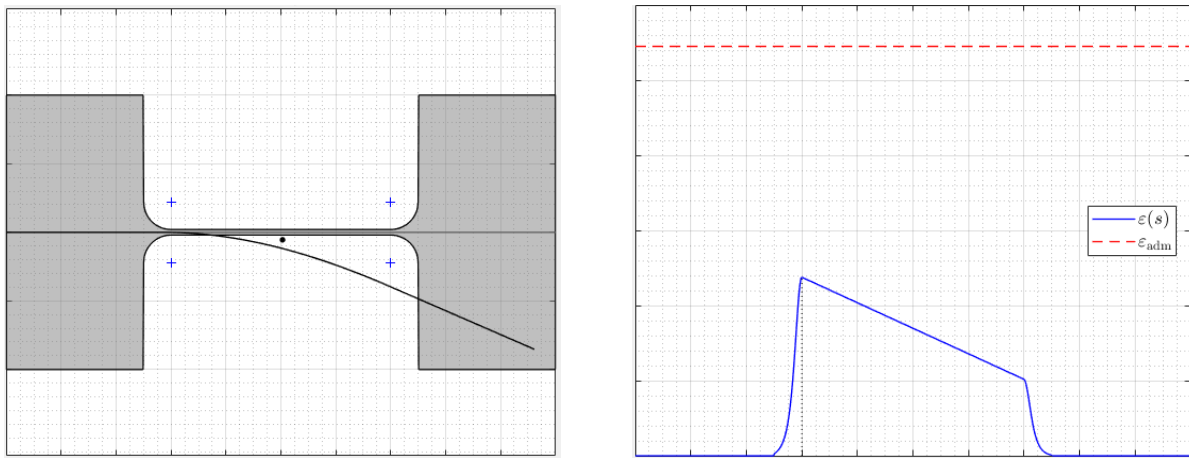


Figure 8: Geometry plot and strain distribution plot (AMLOY-ZR01: 0,94 distance until ε_{adm})

If the deflection line is compared with the geometric representation, the ratio of the young's modulus becomes clear. At the same load, the deflection of the amorphous metal is the highest. At the same time, combined with the observation of the strain distribution plots, it becomes clear that for the amorphous metal a further possible strain on the deflection line up to the elastic limit is the greatest. This becomes clear in the distance of the blue line of the stretched deflection in relation to the path to the red dashed line which describes the admissible elastic strain in which the solid joint is not irreversibly deformed. It is clear from the comparisons of the plots that, in contrast to conventional materials like hardened or stainless, amorphous metals, due to their unique material properties, can show its advantages in increasing performance in compliant systems and thus, as in the case of TRUMPF's solid-state joint, can offer significant added value in solving previously unsolvable challenges.

RESULT: EXPANDING AND ENABLING THE DESIGN HORIZON

As seen, compliant systems and flexure elements made out of amorphous alloys offer a number of advantages that make the use of amorphous alloys indispensable for the efficient use of solid-state hinges due to the described stress field. The component-related presentation of the TRUMPF application also makes it clear that development processes can even be accelerated and promoted with new materials. It remains to be said that amorphous alloys with the properties described and summarized in the following portfolio are used precisely when conventional materials are limited in their properties and applications need to be enabled to generate solutions:

Resilient material behavior

- High bending strength (up to 2000 MPa)
- High directional elasticity (up to 2%)
- Low poisson's ratio ν (0,35)

Design optimization

- Miniaturization (web width, overall)
- Complex geometries with tight tolerances
- Thinner walls with same strength and better elastic functionality

Environment independence

- High corrosion resistance (passivation and no phase / grain boundaries)
- Low thermal heating (low thermal conductivity)
- Low temperature ductility (for cryogenic mechanisms in space)

Sensitivity enlargement

- Increase of measurement sensitivity / positioning accuracy
- High resolution and repeatable mass movement
- Low hysteresis

Viable and reproducible manufacturing process

- Complex geometries in selective laser melting
- Tight tolerances without significant shrinkage in injection molding
- Cost- and time- effective manufacturing method for flexures

Biocompatibility

- For applications in food and pharma industry

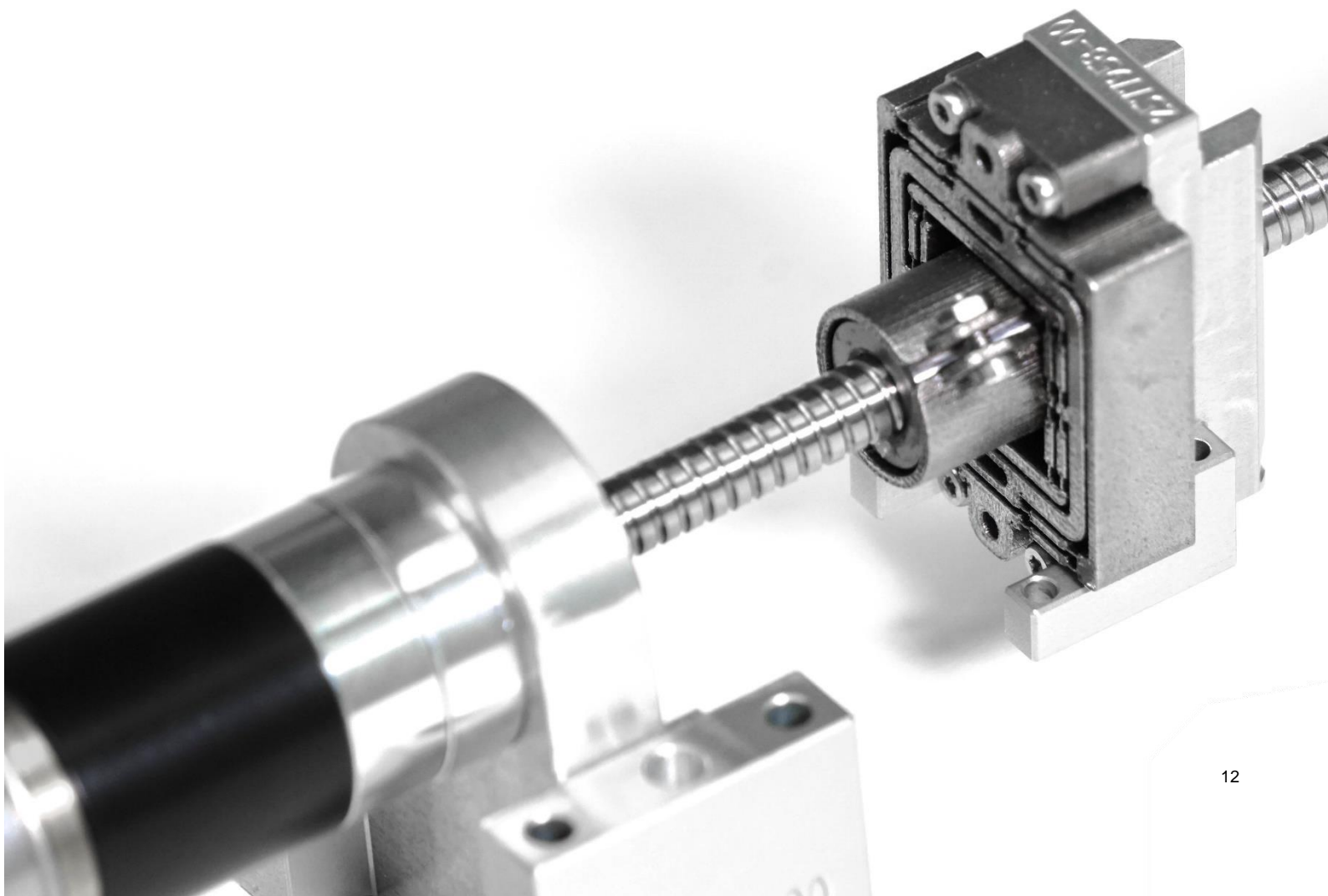
OUTLOOK: POTENTIAL TO EXPLORE

Not only hinges in the sense of revolute pairs can be upgraded in performance from the classic rigid-body system with compliant hinges, but also prismatic or translatory movements or even screw arrangements and rotational movements can be mapped in compliant systems. Applications range from microgripper control units to positioning and weighing systems. An exciting application can also be seen in cryogenic space applications for compliant systems made of amorphous alloys due to their low-temperature reliability. From actuators to sensing applications, a variety of potentials and benefits can be found by combining 3D printing, compliant mechanisms and amorphous alloys.



If we understand the great potential of amorphous alloys in terms of their property portfolio and application potential, we can find solutions that previously seemed economically unsolvable.

– Arne Steck, Design Consultant Additive Manufacturing at TRUMPF



START YOUR AMORPHOUS JOURNEY NOW

About Heraeus

Heraeus, the technology group headquartered in Hanau, Germany, is a leading international family-owned portfolio company. The company's roots go back to a family pharmacy started in 1660. Today, the Heraeus group includes businesses in the environmental, electronics, health and industrial applications sectors. Customers benefit from innovative technologies and solutions based on broad materials expertise and technological leadership.

About Heraeus AMLOY

Heraeus AMLOY specializes in the development of amorphous alloys and the production of amorphous components. These enable completely new high-tech applications due to their unique material properties such as high strength combined with high elasticity as well as corrosion resistance and biocompatibility.

In the 2020 financial year, the FORTUNE Global 500 listed group generated revenues of €31.5 billion with approximately 14,800 employees in 40 countries. Heraeus is one of the top 10 family-owned companies in Germany and holds a leading position in its global markets.

Heraeus AMLOY's near-net-shape process solutions injection molding and 3D printing are ideally suited for industrial production

amloy@heraeus.com | +49 6181 35-9650 | www.heraeus-amloy.com

About TRUMPF Consultant Additive Manufacturing

Whether it's about getting started with the technology, identifying and developing suitable parts or optimizing your production - at TRUMPF Additive Manufacturing, you can always count on competent support along the entire AM process chain.

Our comprehensive portfolio of training and consulting services, enables you to quickly learn and apply new methods and thus enter the additive manufacturing of your part optimally prepared. Become more economical, more efficient and of higher quality— we support you!

Consulting.am@trumpf.com | +49 7156 303-31620 |
www.trumpf.com/s/am-consulting

