Heraeus

AMLOY

Whitepaper

AMORPHOUS ALLOYS MEET SENSOR COMPONENTS

IMPROVING ACCURACY AND SENSITIVITY

01 HIGH REQUIREMENTS PUSHING NEW MATERIAL SOLUTIONS

In many areas of today's high-tech applications, conventional materials are reaching their performance limits. This is mainly due to the high challenges arising from the complex and demanding tasks of future applications. Often, the requirements have increased faster than the development of adequate materials.

This is the case with sensing devices, too. The trend towards miniaturization and the reduction of installation spaces is limited by material properties and the corresponding design freedom. One of the biggest material challenge is to find the optimal combination of sensitivity and fatigue strength. Additionally, it is not uncommon, that other indispensable properties such as high corrosion resistance, antibacterial surface quality and low thermal influence correlate with a sensor application.

These challenges are accumulating in the field of pressure sensors. Pressure sensors measure the pressure of gases or liquids often in a challenging environment and operate by generating an electrical signal as a function of pressure. Such pressure sensors are often referred to in pressure transducers, pressure transmitters, pressure indicators, piezometers or manometers.

In this paper we focus on resistive sensor elements, their challenges and potential solutions.

> *"Measure everything that is measurable and make measurable what is not yet measurable."*
>
> *- GALILEO GALILEI*

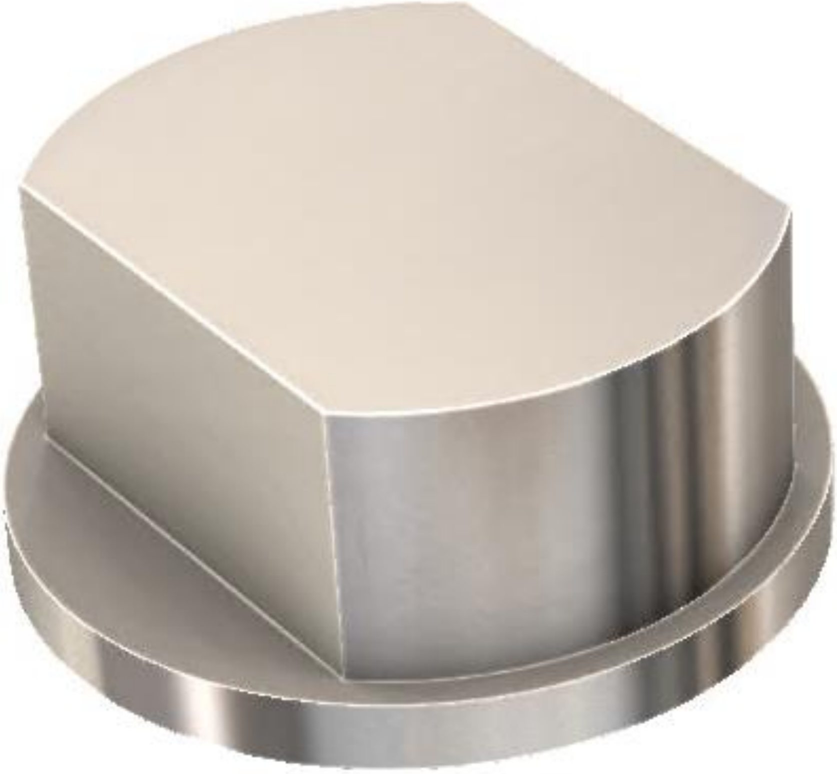


Figure 1: Base element of a metal thin-film sensor

02 RESISTIVE SENSOR ELEMENTS

The sensors described in this context refer exclusively to the measuring principle of resistive sensors. However, applications in the areas of overload protection, cost-benefit alternatives to resource-intensive piezoelectric measurement or simply as permeable stabilization of magnetic field sensors are also conceivable.

The most common applications in these fields are the thin-film sensors. Here, four resistors are arranged on a membrane in the form of a Wheatstone bridge to detect the deformation of the membrane under pressure. In the thin-film process, these strain gauges are applied to a base element (see figure 1) and structured (sputtering with associated photolithography and etching possible for amorphous alloys). The operating principle of resistive sensors is simply explained: depending on the measured variable, the ohmic resistance at a sensor application changes. This change in resistance leads to a change in the voltage drop across the sensor which is then detected with voltage dividers and strain or even optically using laser systems. The knowledge of the effect of the change in electrical resistance due to mechanical strain is applied.

In the field of metal strain gauges, a distinction is made between wire strain gauges, foil strain gauges as well as thin-film strain gauges. Based on the principle of strain gauges, torque transducers, pressure sensors, force transducers and even load cells can be efficiently designed.

Typically, thin crystalline metal materials are used that either act as electrical conductors or use strain gauges or piezoelectronics to measure the current flow on contact to detect the change and thus generate a signal. It is, of course, possible to compare materials for a given wall thickness or component thickness by using, for each material, the ratio of its elastic limit to its elastic modulus. The ratio here is representative for the elastic deformation of each material. The higher this ratio, the greater the elastic deformation for the same geometry and loading of the materials.

Above a certain stress, defined as the yield strength, metallic material deforms irreversibly and thus becomes inelastic. This plasticity impairs function and utility. Crystalline materials such as stainless steel or titanium typically have a low ratio and consequently a limited ability to exhibit elastic deformation and eventually fail after repeated use.

Metallic strain gauges are therefore based on the change in resistance due to changes in length and cross-section. When stretched, resistance increases, and when compressed, resistance decreases. The challenge is to apply the strain gauges to the test specimen using a suitable adhesive or even sputtering techniques. Typical disturbances resulting from the material of the base body are temperature, creep, transverse contraction, hysteresis and magnetic fields.

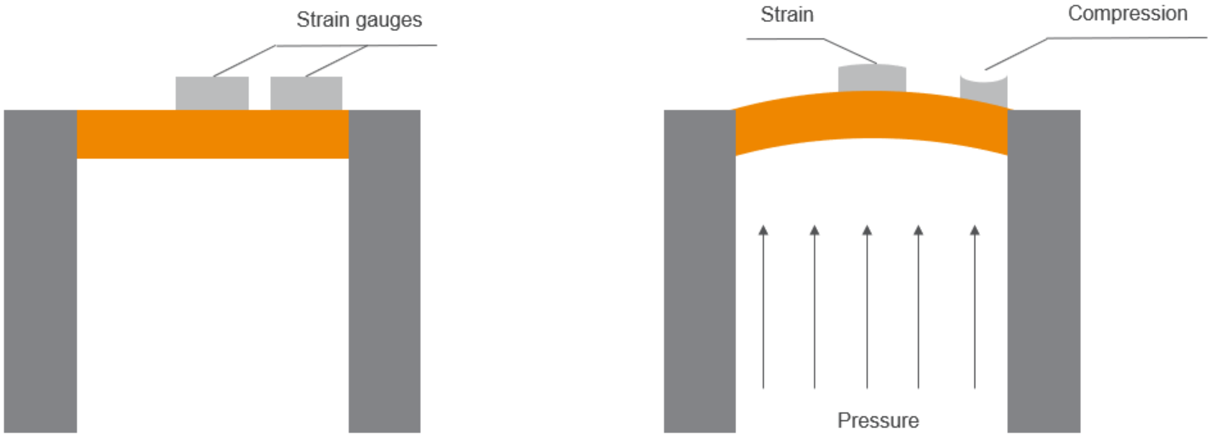


Figure 2: Functional principle of a thin-film coated strain gauge

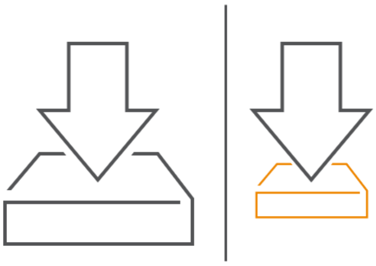
03 CHALLENGES

Sensitivity

- Basic force required to achieve linear measuring range
- Fine resolution not realizable
- Low pressure ranges can only be roughly represented
- Small load differences are only roughly represented

Strength & Fatigue Strength

- Allowable stress
- Fast reaching of overload ranges and bursting pressure

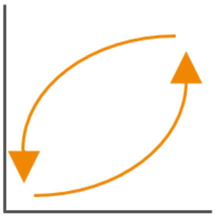


Miniaturization

- Walls and thicknesses
- Lightweight construction and smaller installation space
- Cost-effective design adjustments

Corrosion resistance

- Long-term protection through passive layer
- Handling of aggressive media



Hysteresis

- Influence on component performance
- Large effects of delayed behavior

04 AMORPHOUS ALLOYS – THE MATERIAL SOLUTION

Unlike conventional metals, which solidify as they cool from the melt and form a crystalline structure that shows up in regular lattices, amorphous structures are formed by cooling the molten metal sufficiently quickly while avoiding crystallization. This structure has the advantage of lacking the grain and phase boundaries that conventional metals have. Without these weak points, the material is exceptionally corrosion resistant and even biocompatible. In addition, as mentioned earlier, metallic glasses combine properties that were previously mutually exclusive. They have a higher strength than conventional steel and a higher elasticity than spring steel. At the same time, they are highly resistant to abrasion and wear.

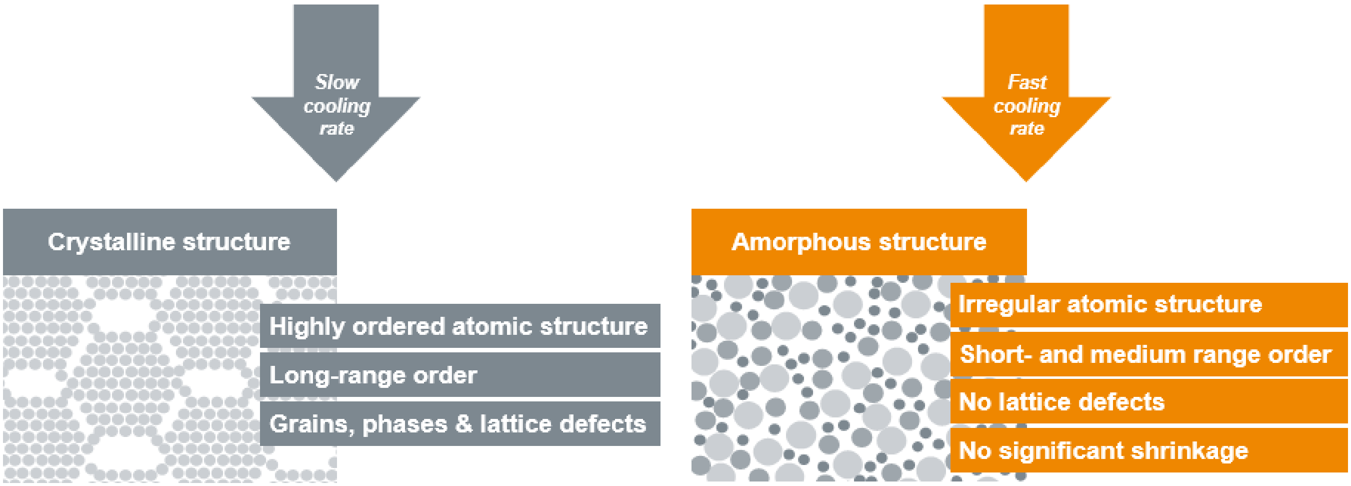


Figure 3: Crystalline structure vs. amorphous structure

Amorphous alloys have the ability to absorb and release large amounts of energy, which make them exceptionally elastic. Complex geometries with high surface qualities and tight tolerances can be produced because shrinkage during solidification is less than 0.5%. This enables single-stage manufacturing technologies such as injection molding or 3D printing to be suitable for reproducible series production in high qualities.
By using these unique properties, lightweight constructions and miniaturization become possible. Amorphous alloys can be used in applications ranging from medical technology and aerospace to robotics and the lifestyle industry.

It becomes particularly exciting for the sensor industry when specific characteristic values are considered, first and foremost, the high energy storage capacity which results as the modulus of resilience U_r. It describes the amount of energy per unit volume that can be stored and released by the material without permanent deformation (see for visualization figure 4 and for data analysis

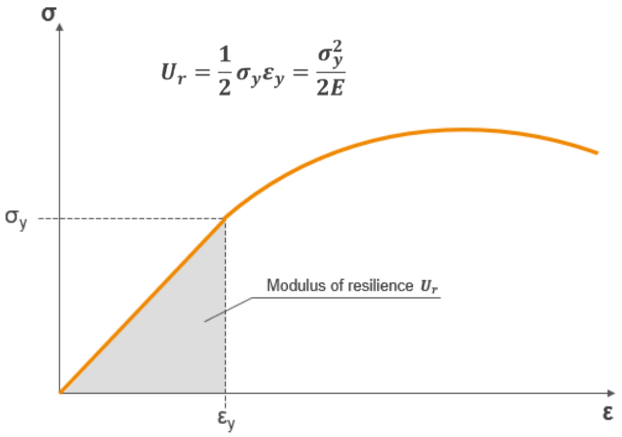
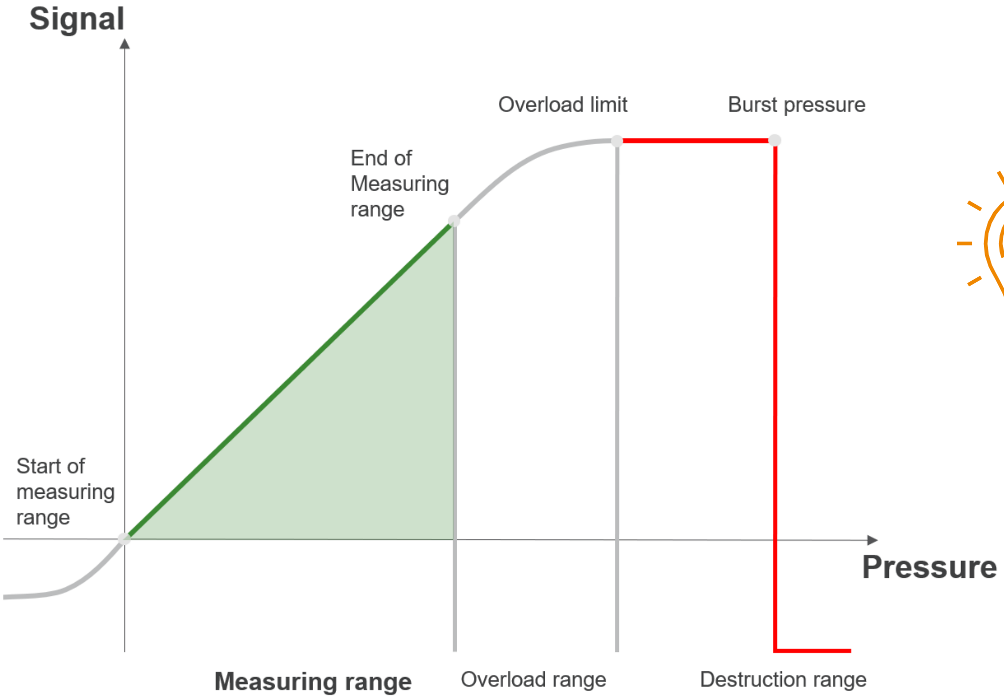


Figure 4: Determination of the modulus of resilience

One solution to optimize pressure sensors is to use amorphous alloys as the basic element of the required deformable materials. Shaping is ideally done in an application-oriented geometry, where the resulting deformation as a function of pressure is recorded optically via laser gauges or physically via applied strain gauges (achievable by sufficient adhesion through bonding or sputtering).

These recording systems emit a corresponding signal based on the change in resistance due to stretching or compression. Due to their excellent elastic deformation of up to 2% combined with very high yield strengths (tensile about 1.6 GPa and bending about 2.3 GPa), amorphous alloys have the best prerequisites for taking future sensor applications to a new level in terms of their general sensitivity, accuracy even in the low-pressure range, and continuous stress even in highly sterile environments due to their certified biocompatibility.



Key to **ideal measuring range** and accuracy
=
Large, defined and reliable **elastic material behavior**

Figure 5: Definition of general pressure measurement areas

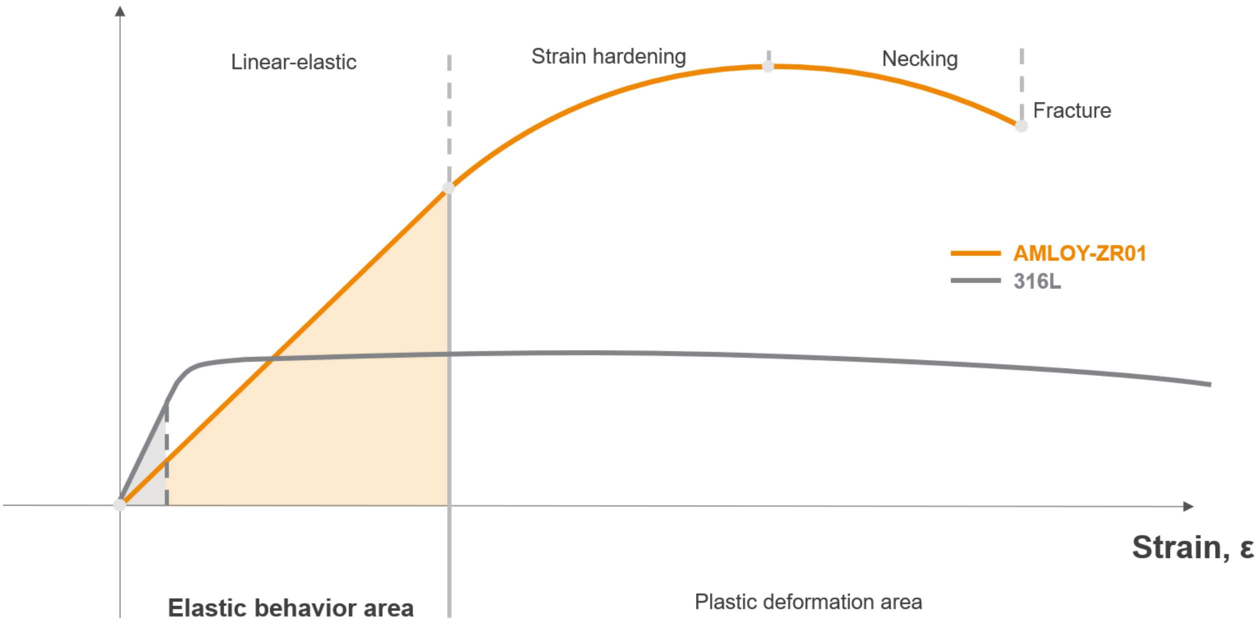


Figure 6: Comparison of idealized stress strain curves

05 AMORPHOUS ALLOYS EXPANDING MATERIAL LIMITS

In combination the comparably lower modulus of elasticity results in a higher elongation and thus sensitivity or accuracy under the same load and geometry. All these properties result in the advantageousness of components made of amorphous alloys in the areas of suspension or damping under high load, which is one of the core topics in the sensor technology.

An overview of the mechanical properties of components made of the amorphous alloy AMLOY-ZR01 in comparison to conventional sensor diaphragm materials can be found in the following diagrams:

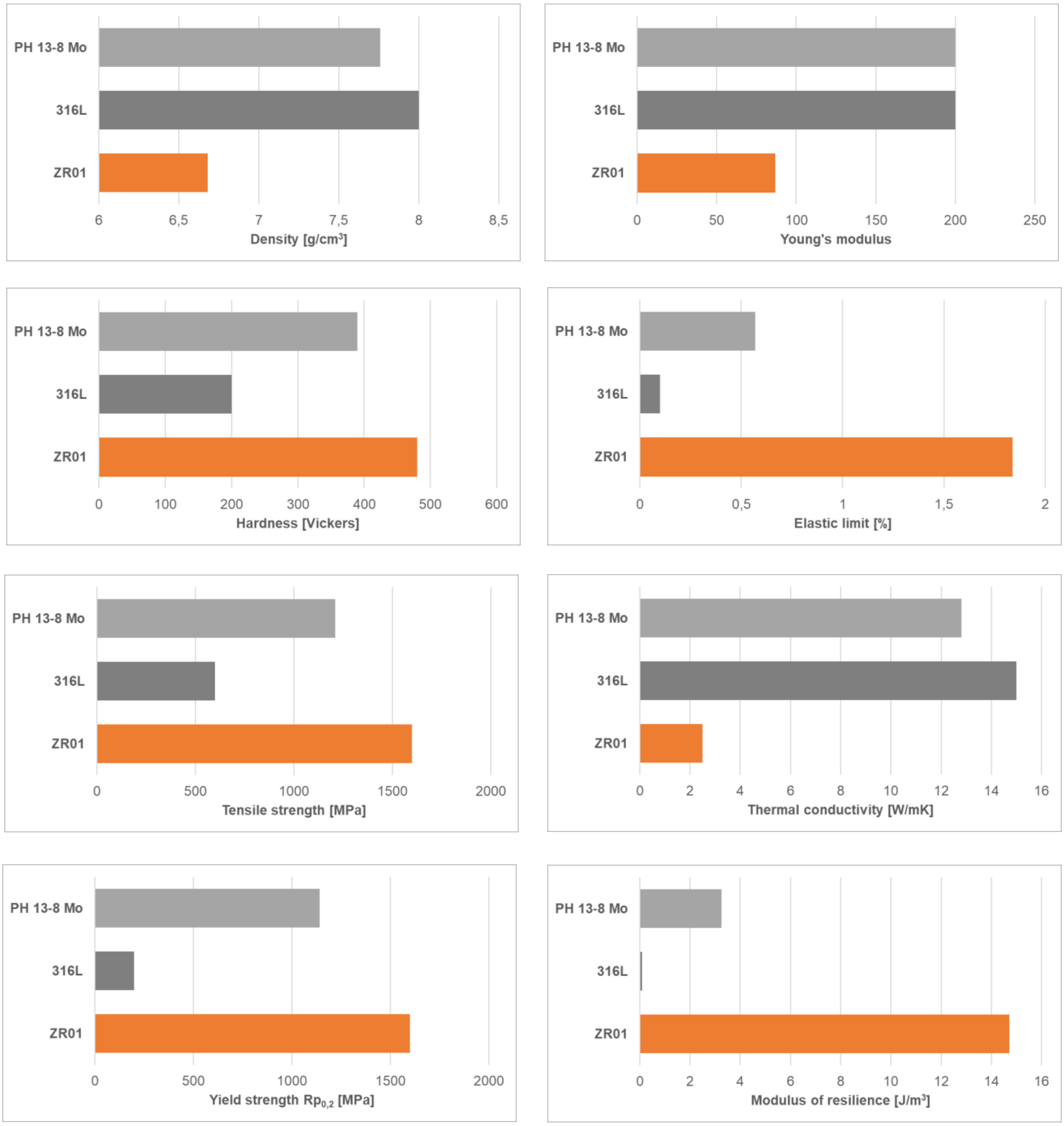


Figure 7: Mechanical properties of AMLOY-ZR01 in comparison to PH 13-8Mo and 316L

06 AMORPHOUS ALLOYS IMPROVING YOUR SENSOR

Considering the challenges posed by sensor technologies in terms of metrology, as well as material selection, while adding the potential material field of amorphous alloys, a positive overlap emerges that improves sensor applications in their design, usage, and part life time. The details of this overlap are disclosed and discussed below. SAE 316L stainless steel as well as PH 13-8 Mo (precipitation hardening stainless steel) are used as references. These materials are typically used for diaphragms in pressure sensors, depending of course on the measurement range, environmental conditions and resolution.

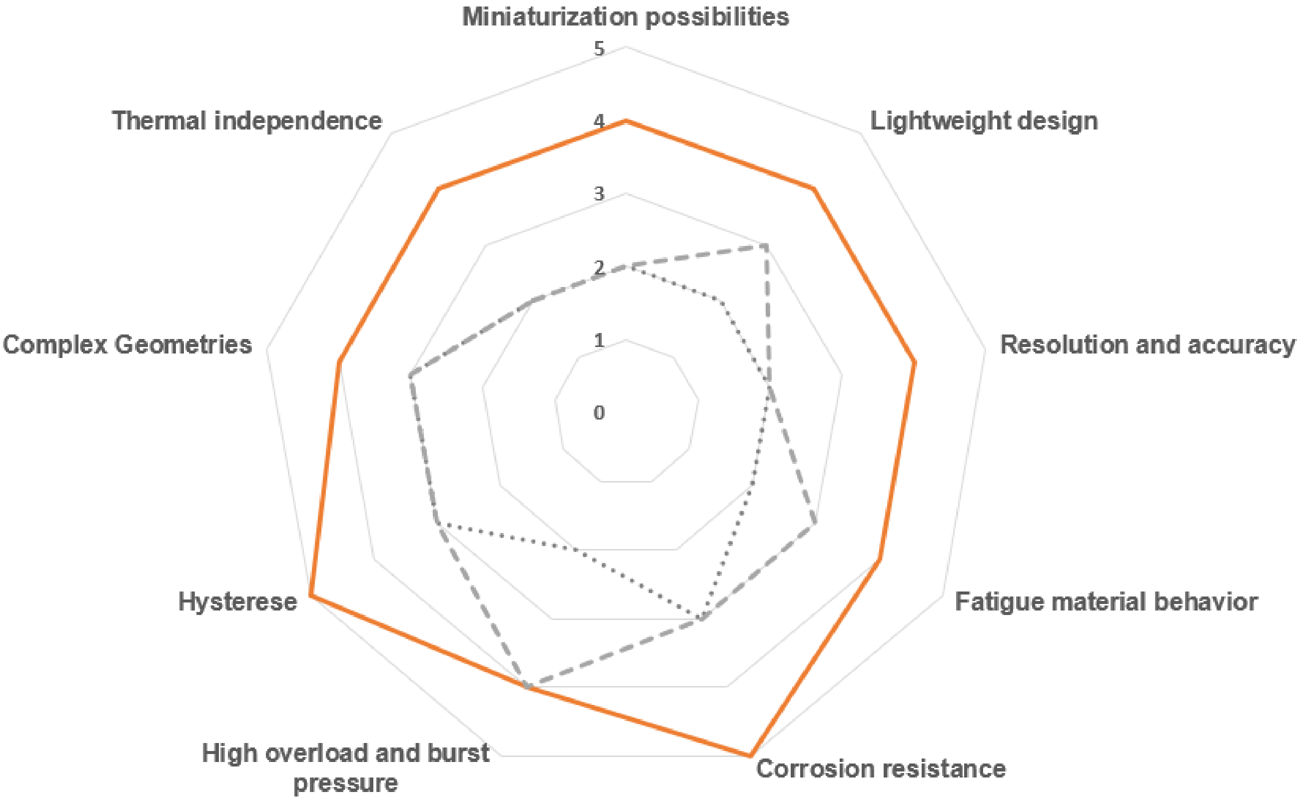


Figure 8: Overview of the property portfolio in terms of sensor applications and materials

Figure 6 illustrates the overall potential of amorphous alloys as a material for sensor technologies. In addition to the higher radial stress, the ratio of Young's moduli in the linear theory allows miniaturization of the dimensions of sensor components and thus also of assemblies with the same load and geometry. This miniaturization in combination with lower density results in the possibility of promoting lightweight construction of these components for weight-critical applications, e.g. in aerospace. The high elastic deformability also leads to measurably higher resolution and accuracy in the measurement range. Both small pressure differences and environments with extremely low pressures can be reliably analyzed.

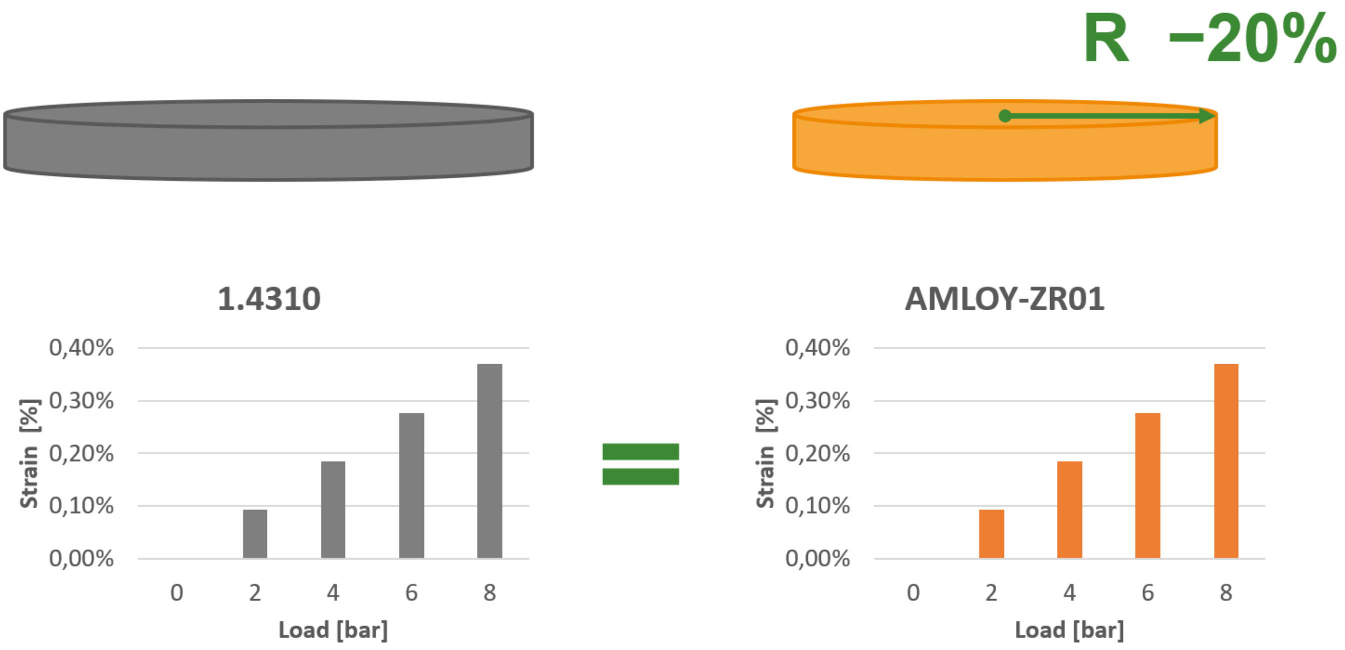
Furthermore, when considering the fatigue behavior of materials, reliable strain at high cycle numbers is also important. Here, amorphous alloys stick out with a long-term stability of 200-400 MPa and a resulting strain of 0.24% to 0.47%. In comparison conventional steels are higher with a long-term stability of 420 MPa, but the strain of 0.21% is already below the high resolution of amorphous alloys.

Due to their excellent passive layer and lack of grain and phase boundaries, amorphous alloys are also very corrosion resistant. Thermal independence, provided that handling takes place below the glass transition temperature of approx. 400°C, ensures reliable material behavior due to its low thermal conductivity. This reliability also includes the low hysteresis, which comes into play due to the good recovery behavior of amorphous alloys. Even with larger wall thicknesses, which contribute to improved overload and bursting pressure behavior, identical deformation behavior can be achieved as with comparable materials at the smaller dimension. As a result, safety factors can be increased and even complex geometries can be reproduced.

Smaller dimensions ✓
(up to 20%)

(at same load and elastic deformation)

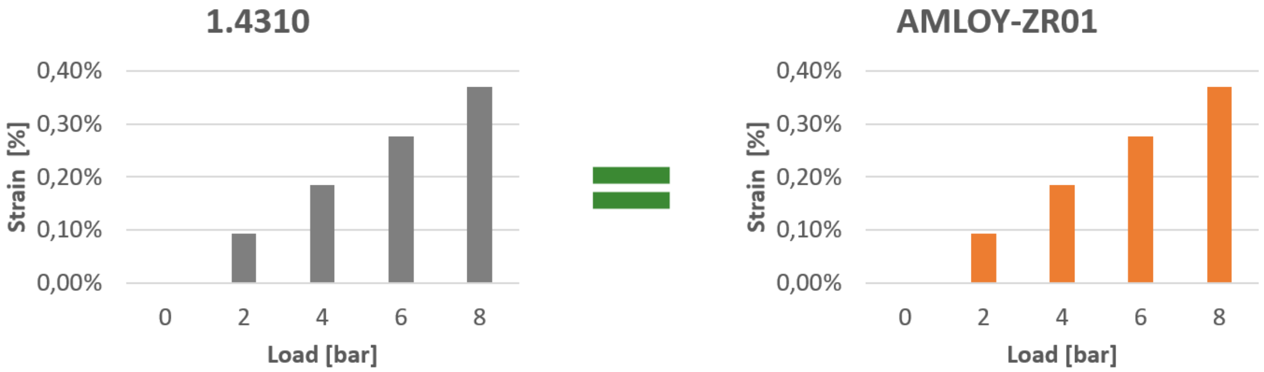
- Smaller diaphragm diameter
- Smaller measuring elements
- Lighter measuring elements



Wall thickness ✓
(1.5x)

(for same elastic deformation and load)

- Higher overload and burst pressure
- Higher load cycle strength



High corrosion resistance ✓

(compared to conventional materials)

- Direct contact with aggressive media possible
- Long-term resistance

High overload and burst pressure ✓

(without plastic deformation)

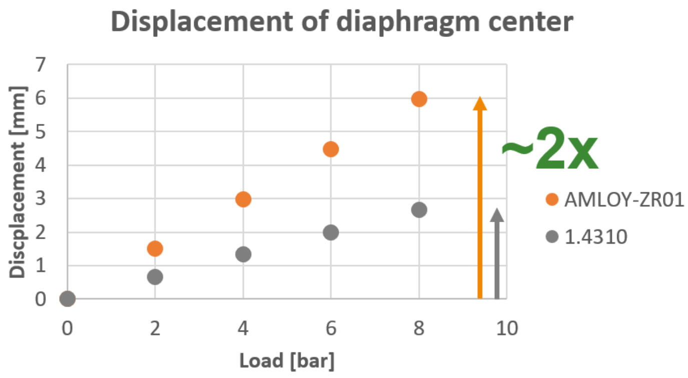
- Higher allowable stress and load
- Greater permissible elastic elongation

Elastic deformation ✓

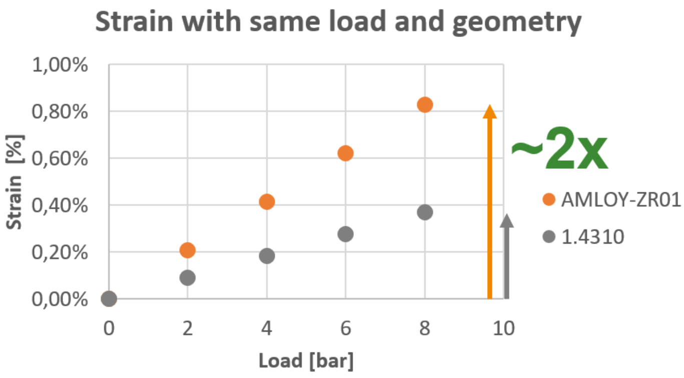
(2x)

(at same load and geometry)

- Higher overall accuracy
- Higher resolution in low pressure ranges



Displacement of diaphragm center



Strain with same load and geometry

Temperature resistance ✓

- No significant temperature effects
- Higher stability in low temperature ranges (low temperature ductility)

Complex geometries ✓

- With materials as manufactured without complex post-treatment
- Enabled by injection molding or additive manufacturing (3D printing)

Low hysteresis ✓

- Compared to conventional materials

Biocompatibility ✓

- Antibacterial surface quality

07 OUTLOOK

Previous findings have shown that there is sufficient potential for the use of amorphous alloy components in sensor technology. With the combination of unique material properties and an enhancement of the sensory effect in the resistive principle of action, previous boundaries can be completely redesigned.

As mentioned at the outset, however, this is not the only area in which the material class of amorphous alloys is developing its potential. In the areas of overload protection, where small pressure differences have to be measured in high pressure ranges, they open up new possibilities. The cost-benefit alternative to expensive piezoelectric measurement or the permeable stabilization of magnetic field sensors also leaves room for innovation through pioneering materials technology. Force transducers such as load cells can be designed to be more sensitive and smaller. Torque sensors with the presented technology of applied strain gauges can also be improved in the areas of continuous load and sensitivity. Even highly sensitive microfabricated pressure devices (candidates for electronic monitoring systems in health, human motion, safety, etc.) are also exciting applications that amorphous alloys can enable.

The results presented show that amorphous alloys can be an option for stretchable sensing applications. We are therefore convinced that metallic glass will be a key material for high-tech sensing.

Heraeus AMLOY

START YOUR AMORPHOUS JOURNEY NOW

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About Heraeus

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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.

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.

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