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High performance metal alloys for renewable energy

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Renewable energy encompasses a wide range of technologies, each requiring specialized materials. Understanding these materials and their applications is crucial to determine the necessary properties and how to characterize them to prove their utility. This work is twofold: it begins with an introduction to the renewable energy sectors, general requirements, and the materials to be discussed later. The main part outlines the contribution of selected materials, namely copper alloys ($CuBe_2$, Cu15Ni8Sn), beryllium, niobium, tantalum and clad metals, in enabling these technologies. Applications from different energy sectors are considered, with examples ranging from small devices such as bearings, switches, and sensors to key components like bipolar plates in fuel cells. The relevant materials and their properties, which ensure functionality, reliability, and longevity, are presented to demonstrate that high-performance materials are indispensable for the green energy revolution. The performance of the material is thanks to its chemical composition and, in many cases, to tailored nanostructures, such as ultrafine precipitates in case of $CuBe_2$ or chemical segregations at the atomic level in case of Cu15Ni8Sn.

Keywords: Renewable energy; Batteries; Hydrogen; Metals.

1. INTRODUCTION

The US Department of Energy defines seven types of renewable energy: bioenergy, geothermal energy, hydrogen and other renewable fuels, hydropower, marine energy, solar energy and wind energy [1,2]. Nuclear energy is not generally considered renewable, but some organizations and countries have recognized its role in the global energy mix. So, in 1987, the Brundtland Commission (WCED) classified fission reactors that produce more fissile nuclear fuel than they consume (breeder reactors, and if developed, fusion power) among conventional renewable energy sources, such as solar power and hydropower [3]. The EU Green taxonomy even goes a step further and includes nuclear energy as one of the options to reduce the CO_2 footprint of energy production [4]. What all these applications have in common is that they require high efficiency, reliability and a long service life. Nevertheless, each specific application results in different sets of requirements for the material solutions [5]. These may include (see Table 1):

- Sufficient strength and fatigue strength
- High wear resistance in sliding applications such as bearings [6], for instance
- Elevated temperature stability, e.g. high temperature strength, relaxation/creep resistance
- Corrosion and oxidation resistance at both room temperature and elevated temperature
- High electrical conductivity
- High thermal conductivity
- Defined optical properties
- Nuclear properties such as transparency/reflectivity for neutrons and degradation properties when exposed to radiation

Table 1 Material requirements and for which energy these are of major relevance [5].

Requirement	Types of renewable Energy
Mechanical strength	Miscellaneous
Fatigue strength	Miscellaneous
Wear resistance	Miscellaneous
Stability at elevated temperatures	Geothermal, hydrogen, nuclear, solar
Corrosion resistance	Biogas, geothermal, hydrogen, offshore / subsea, hydropower
Electrical conductivity	Batteries, electrical energy, hydrogen, solar
Thermal conductivity	Miscellaneous
Optical properties	Solar
Nuclear properties	Nuclear

The idea behind renewable energy is to use natural resources to generate electricity and heat residential buildings. The use of renewable energy is based on locally available resources. This leads to strong local diversification in technological approaches. For example, in the African region, South Asia and Australia, most of the renewable energy is generated by solar energy, which is not surprising given the high number of hours of sunshine there. Hydropower dominates in Brazil, Canada, parts of Northern Europe and the Alps. Wind energy is ideal for regions further away from the equator and therefore makes a significant contribution to renewable energy in Argentina, parts of the USA, China and the North Sea region [7].

Europe plays a crucial role in the global economic and energy systems, yet its energy landscape is highly diverse. This diversity stems from significant variations in population, economic status, and energy resources among its individual countries. Regulations also have a significant impact in Europe. Nevertheless, some regional trends can be identified. In Northern Europe and the Alpine region (Austria and Switzerland), hydropower accounts for a high share of renewable energy. In Germany, Ireland, Portugal, and Spain, wind power accounts for the largest share. Natural gas and nuclear energy are also playing an increasingly important role in many European countries. Furthermore, many of Germany's neighboring countries have viewed nuclear energy as an indispensable energy source in the past [8]. All these aspects naturally also influence the selection and development of materials for the energy sector, especially regarding renewable energies. This will be discussed in more detail in the next chapter.

2. Importance of high-performance materials for renewable energy

2.1 Overview

Materials are essential to the effectiveness, reliability, affordability and longevity respectively sustainability in the production of renewable energy. According to Vidal et al. [9], the energy transition requires various raw materials – not only certain more specialized metals such as cobalt, nickel, or indium, but also common metals such as aluminum, copper, and iron. For this reason, it makes sense to categorize all these materials into two groups [10]:

- Base materials: They are used in almost all energy sectors for a wide range of applications and account for a large proportion of material consumption in the generation of renewable energy. Prominent examples are steel, aluminum and copper.
- Specific materials: Certain materials are essential for one or a few technologies and are therefore often referred to as functional materials [11]. Examples include rare earths for permanent magnets, silicon and tellurium for solar modules, lithium and cobalt for batteries, and platinum group metals and scandium for hydrogen.

Fundamentally, it can be observed, perhaps surprisingly, that the global energy transition is highly material-intensive, especially metal-intensive. Electric vehicles, batteries, photovoltaic systems, wind turbines, and hydrogen technologies require significantly more metals than their conventional alternatives to meet the demand for fossil fuels [10]. For example, a wind turbine or a photovoltaic system requires 90 times more aluminum and 50 times more iron, copper and glass than a fossil-fired power plant with one megawatt of power [12]. However, material efficiency plays a crucial role in the overall balance. It should be noted that the material requirements per megawatt-hour of generated renewable energy are not significantly higher than those for fossil fuel generation. On the contrary: technologies such as wind power, hydropower, or solar energy even achieve significantly higher material efficiencies, although the material efficiency in some technologies might also depend on their installed capacity. Another important finding is that functional metals such as lithium and cobalt have a negligible impact on material efficiency in wind, solar and hydropower technologies [13].

In addition to these general considerations, it is worth briefly examining the renewable energy sectors to identify some differences. The starting point for this consideration is solar energy, which is based primarily on semiconductor elements such as silicon for photovoltaic cells, which convert the sun light into electrical current [14]. However, solar energy encompasses much more than just photovoltaic cells. There's also a wide range of peripheral devices that also require the right materials. These include electrical connectors, switches, sensors, and cooling devices [15]. The metals used in solar energy therefore include aluminum, copper, zinc and silicon (base metals) as well as rare earths, semiconductor metals, tin and tellurium (functional metals) [10].

Wind energy is another vital source of renewable power. The production of strong, durable magnets for wind turbines requires rare earth elements. Additionally, wind turbines include components like turbine blades and journal bearings, where material selection is crucial due to the importance of friction and wear [14]. In summary, the most relevant metals for wind energy are aluminum, copper and zinc (base metals) as well as rare earths (functional metals) [10].

In hydropower and biomass, materials such as nickel alloys and copper bronze alloys provide the corrosion resistance required for these applications [14]. Corrosion is also crucial in geothermal energy. New pipe materials for deep geothermal wells must withstand the extreme heat-corrosion conditions of the fluids used for heat transfer in geothermal systems [16]. In these aspects, in addition to aluminum, copper and zinc, high-melting metals such as nickel and cobalt also come into play [10].

Nuclear power is one of the most mature, zero-emission, low-carbon power generation technologies. It is being driven by the development of a new generation of molten-salt reactors that enable greater safety. Another aspect of advanced nuclear power is small modular reactors (SMRs) and microreactors, which have significantly lower power and require less space than conventional nuclear power plants. These enable new applications that offer greater mobility and therefore flexibility. Advanced materials ensure more reliable performance at higher temperatures, in more corrosive environments, in stronger radiation fields, and over longer periods [16]. This application also requires special metals such as beryllium and refractory metals [10].

The energy transition affects not only the electricity and heat production itself, but the entire energy system. A key challenge is that corresponding energy sources such as wind and solar power are inevitably subject to natural fluctuations, yet the energy supply must be also guaranteed even when production is low. Sustainable storage technologies such as batteries or fuel cells serve as intermediate storage to bridge potential supply gaps [11,17]. Battery technology for energy storage is largely based on lithium-ion batteries, which will remain relevant in the future. At the same time, intensive work is underway on a new generation of "post-lithium batteries" [18]. Aluminum and copper are the most important base metals for batteries, with lithium, nickel, and cobalt being added as functional metals [10]. With the development of new battery technologies, additional elements such as sodium, phosphorus, and silicon will be added.

Hydrogen fuel cells offer another promising solution for energy storage by converting the stored energy in hydrogen into electrical power through an electrochemical process [16]. They utilize a variety of materials, including those for the membrane, electrodes, catalysts, and structural components. Key materials include aluminum, copper and steel (base metals) as well as cobalt, graphite, platinum, lithium, nickel palladium, iridium, ruthenium and titanium (functional materials) [10].

Most renewable energy applications have not yet reached their full development potential and are subject to constant innovation. This is due, among other things, to the following reasons [14]:

- Efficiency gap of existing technologies
- Technical shortcomings of existing technologies in terms of reliability, longevity or security
- Scarcity of resources and reliability of supply chains
- Cost reduction
- Political regulation

These factors fuel topics such as alternatives to lithium-ion-batteries (elimination of the use of critical materials like cobalt or nickel using Lithium Iron Phosphate batteries, increase safety) [19], alternatives to platinum in fuel cells (use of clad metals for cost reduction) [16] and materials that offer lower friction and increased wear resistance to improve efficiency and longevity in sliding applications [18].

2.2 Material groups covered in this publication

Renewable energy uses a wide variety of materials, particularly metallic ones. As expected, each materials manufacturer covers only a portion of this spectrum. This also applies to Materion Corporation, whose materials are therefore the focus of this publication. They include pure metals such as beryllium, copper alloys like $CuBe_2$ and Cu-15Ni-8Sn, refractory metal alloys of tantalum and niobium.

- Pure beryllium: Although beryllium counts as a metallic element, it is unique in comparison with other metals due to strong atomic bonding. As a result, beryllium provides extraordinarily high strength and high thermal conductivity. Very specific to beryllium, it is practically transparent

for X-rays, has only a small capture cross section for thermal neutrons, but a high scattering cross section [20,21].
- Beryllium-copper alloys: Typically, these alloys contain 0.2 to 2.0 mass-% beryllium and can be alloyed with further elements such as cobalt or nickel. After forming and heat treatment (solutionizing and tempering) most of the beryllium is distributed in fine precipitations (CuBe) which contributes to high strength, fatigue strength and relaxation strength. At the same time, there is a low content of solid solutions left in the copper matrix and by that high electrical and thermal conductivity is achieved. Another benefit of these materials is their good corrosion resistance due to the high copper content and the passivation effect of beryllium [22]. Beryllium copper is particularly resistant to hydrogen embrittlement due to the low solubility and permeability of hydrogen in this material [23].
- Copper-nickel-tin: These alloys provide an excellent combination of strength and relaxation strength, toughness and corrosion resistance in various environments. This outstanding combination of properties applies to a wide range of service temperatures, starting at the lower end at cryogenic temperatures and ending at elevated temperatures of 300 °C and more. This is achieved through a special heat treatment that leads to a so-called spinodal decomposition. Spinodal decomposition occurs spontaneously and as a result there are solute-rich and solute-lean regions next to each other on an atomic scale [24].
- Nickel beryllium alloys: These alloys utilize nickel properties such as strength, temperature resistance, toughness and corrosion resistance, which are further enhanced by the addition of up to 2 mass-% beryllium. Thus, they can withstand periodic temperature increases up to 350°C and regarding tensile strength, no significant deterioration can be observed even up to 600 °C. Further advantages of them are a low temperature degradation of electrical and thermal conductivity up to 350°C, a stiffness and ductility (elongation) comparable to steel, very good corrosion resistance and excellent formability [25].
- Tantalum and niobium: These two belong to the refractory metal family. Due to their high density and high melting temperature, rare earth metals maintain their appropriate strength even at temperatures of 500 °C or even above. Therefore, their physical properties such as electrical conductivity and corrosion resistance only decrease moderately with temperature, as well [26]. The susceptibility of tantalum to hydrogen embrittlement is strongly affected by alloying elements. Small alloying additions of either Mo or Re decrease the corrosion rate and the hydrogen embrittlement, while Hf has the opposite effect [27].
- Aluminum based metal matrix composites (Al-MMCs): Aluminum matrix composites are reinforced with ceramic or elemental particles such as beryllium, silicon or silicon carbide. Therefore, these materials combine high thermal conductivity of the aluminum matrix with high specific strength and stiffness and low thermal expansion due to particle reinforcement [28,29].
- Technical ceramics: Ceramics such as BeO and Al_2O_3 offer several properties that make them attractive for use in renewable energy. These include high temperature stability, high corrosion and oxidation resistance, low thermal expansion and high stiffness [30,31].

Clad metals are another category of high-performance metals. They consist of two or more metals respectively alloys with very different properties, metallurgically bonded by plating, welding or roll bonding and heat treatment. In comparison with single materials, clad metals enable completely new set of properties and much higher performance. The properties can be provided right there where they are needed placing the right material partner [32].

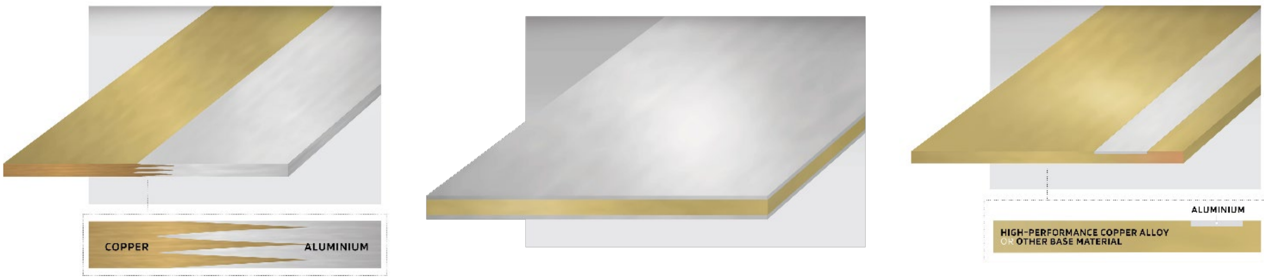
3. EXPERIMENTAL

3.1 Materials

Table 2 displays the materials which will be considered in more detail in this article as being common representatives of the forementioned material classes.

Table 2 Materials discussed in this article for renewable energy applications.

Material group	Representative(s)	Citation
High Purity Beryllium	S-65C	[33]
Beryllium-copper	Alloy 25	[34]
Cu-Ni-Sn	ToughMet 3	[35]
Low alloyed nickel	Alloy 360	[36]
Niobium based alloys	Alloy C-103	[37]
Tantalum based alloys	Alloy ULTRA 76 Plus	[38]
Al-MMC	AyontEX	[39]
Clad metals	Dovetail®	[40]
	eStainless	[41]
	iON EV	[42]



a b c

Figure 1 Overview on different cladding solutions: Dovetail (a), eStainless (b) and iON EV (c).

Typical values of the properties of the forementioned materials are given in Table 3 (physical and other general properties) and Table 4 (mechanical conditions).

Table 3 Physical and other general properties of selected materials (metal alloys and clad metals), value unless otherwise stated at room temperature (RT), for information only, see also references from Table 2.

Material / Alloy	Young's Modulus (GPa)	Solidus temperature (°C)	Electrical Conductivity (% IACS)	Density (g/cm^3)	Thermal expansion ($10^{-6}*K^{-1}$)	Thermal conductivity (W/m*K)
Alloy 25	131	870	22-28	8.4	17.5	105
S-65C	303	1273	40	1.8	14.5	216
ToughMet 3	144	950	5-8	9.0	16.4	38
Alloy 360	195-210	1195	4-6	8.3	14.5	48
AyontEX 4632	94	-	-	2.7	17.1	141
Alloy C-103	90	2350	13	8.6	~4[1)]	90
Alloy ULTRA 76 Plus	186	2996	13	16.7	3.6	55
Cladding: eStainless 240 *	179	-	60	8.5	17[2)]	240[2)]

Thermal expansion from RT to 300 °C. *For Doveteil and iON EV see in results and discussion. [1)]Text. [2)]In-plane.

Table 4 Mechanical properties of selected rod and bar materials (metal alloys and clad metals), further conditions are available, values at room temperature, for information only, see also references from Table 2.

Material / Alloy	Condition / temper	0.2% Offset Yield Strength (MPa)	Ultimate tensile strength (MPa)	Elongation at break (%)	Hardness HRC	Fatigue limit (MPa)
Alloy 25	HT	1000-1310	1210-1480	4-9	37-44	~410
S-65C	-	~250	~370	3-6	-	>214
ToughMet 3	AT 110	≥760	≥875	≥6	≥30	414
Alloy 360	HT	≥1590	≥1860	≥8	-	~700
AyontEX 4632	T6 PGQ	~330	~415	~2	-	-
Alloy C-103	-	~262	~372	~20	-	~260
Alloy ULTRA 76 Plus	-	~250	~350	~20	-	~250-300
Cladding: eStainless 240*	H2	~510	~590	~11	-	-

*For Doveteil and iON EV see in results and discussio.

3.2 Methods of investigation

The basic investigation of the materials included microstructures and mechanical properties. For microstructure characterization, light optical microscopy (LOM) and in some cases electron microscopies are carried out. Tensile testing is performed at room temperature according to ASTM E 8 [43]. The fatigue limit is determined using a rotational bending fatigue test [44].

Further properties depend strongly on the application and are therefore only investigated in the corresponding application cases. This applies particularly to friction and wear, corrosion and chemical compatibility in different environments. Relevant test methods are summarized in Table 3.

Table 3 Test methods for investigation of friction and wear, corrosion and chemical compatibility [45-47].

Material property	Specification	Test method
Stress relaxation resistance	ASTM E328-21	Bend testing
Charpy impact test	ASTM E23	Pendulum hammer
Cavitation erosion	ASTM G32	Vibratory apparatus
Chloride Stress Corrosion cracking	ASTM G36	Immersion in boiling Mg chloride solution
Corrosion under practical conditions	Defined by customers	Field tests
Galvanic corrosion testing	ASTM G71	Electrode potential
Salt spray test	ASTM B117	
Seawater immersion test	ASTM D1141	Immersion in substitute ocean water
Stress corrosion cracking	NACE TM0177 ASTM G49	C-ring test
Stress corrosion cracking	ASTM G129	Elevated temperature slow strain rate test
Sulfide stress corrosion testing (sour service)	NACE MR0175 ISO 15156	Exposition to severe corrosive environments
Hydrogen compatibility	ASTM G148-97	Charging with hydrogen to investigate impact on mechanical properties
Block-on-ring test	ASTM G77	Characterisation of sliding wear behaviour
Galling test	ASTM G98	Coupling two flat samples under compressive load
Bearing test	Defined by customers	Can be bench test or field testing

The test methods in Table 3 refer to specific applications. It is striking that a large number of different methods exist for topics such as corrosion testing. This is because there is no single environment or type of corrosion; rather, conditions can vary from application to application. There exist several test methods instead. These standardized tests simulate harsh environments such as sour gas or chloride-induced stress corrosion cracking which reflect the environmental conditions correlating with specific applications. From these, according to industrial standards a certain set of tests that best fits to the application conditions is used in each case (see also the Results and Discussion).

4. RESULTS AND DISCUSSION

4.1 High strength copper alloys against friction, wear and corrosion in renewable energy

4.1.1 Application conditions and material requirements resulting therefrom

Friction and wear applications such as bearings, joints, slide rails or clutches are used in a wide field of applications. They can already be found in conventional energy, but they are also indispensable for renewable energy applications. In many aspects, the requirements are even more challenging if it comes to renewable energy applications. As an examples, there are given the sliding bearings for wind power engines which are often used for planetary gearboxes and in some designs for main shaft bearings, as well. Table 4 shows typical load conditions for sliding bearings in wind power engines [48-52].

Table 4 Typical load conditions for sliding bearings in wind power engines, values unless otherwise stated at room temperature [48-52].

Material property	Reported value
Sliding speed	0.4 to 10 mm/s
Mean contact pressure	0.5 MPa to 1 MPa
Local contact pressure	30 MPa to 150 MPa
PV value	1 MPa*(m/s) to 5 MPa * (m/s)
Operation temperature	-20°C to 50°C
Maximum contact temperature	≤180°C
Lubricant temperature	~ 50°C
Relative bearing clearance	1 * 10^{-3}
Dynamic lubricant viscosity	90 *10^{-3} Pas
Sommerfeld number	4.7
Lifetime	20 to 25 years

These bearings suffer high contact pressures while the sliding speed strongly depends on the bearing diameter. To make it even more challenging, there are highly variable and complex load conditions due to the fluctuating nature of wind speeds, which results in significant changes in torque and axial loads, often including high radial loads, alternating loading directions, and occasional shock loads, making proper bearing design crucial for reliable operation and longevity [50,51].

To meet these conditions, a material must have high strength, especially under compression, a high threshold against galling and low friction. Another requirement in this application arises from the small relative oscillatory movements in the sliding contacts, which become more important as the bearing diameter increases and make this application susceptible to fretting fatigue. Choosing materials with low friction and high fatigue resistance helps reduce the risk of fretting fatigue [53,54].

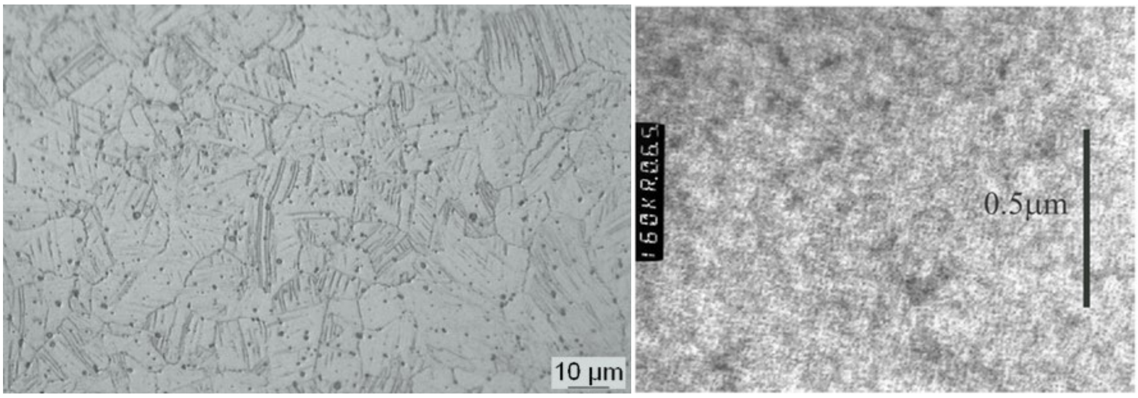


Figure 2 Typical microstructures of Alloy 25 (left) and ToughMet 3 (right), original from internal investigations of Materion Corporation.

4.1.2 Alloy 25 and ToughMet 3: Microstructures and resulting mechanical properties

Alloy 25 (beryllium-copper) and ToughMet 3 (copper-nickel-tin) meet these requirements perfectly. Their outstanding performance in heavily loaded sliding applications is due to a combination of their chemical compositions and their microstructures, which are tailored through the combination of appropriate casting, forming and heat treatment techniques. The casting and hot forming of these alloys results in fine grained microstructures while age hardening further promotes the strength properties due to chemical segregation. In case of Alloy 25, the chemical segregation occurs by means of nano-sized precipitation formation and spinodal composition at the atomic scale is related to ToughMet 3. As a result, these alloys combine high strength and fatigue resistance with high toughness not only at room temperature, but their strength properties are also stable at elevated temperatures of up to 300 °C and even higher [24].

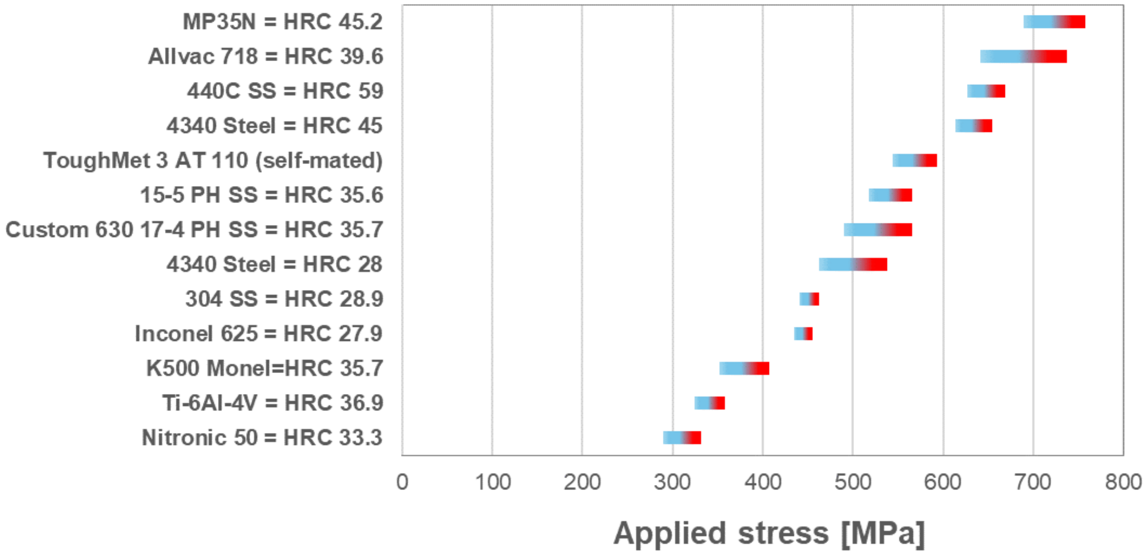


Figure 3 Threshold galling stress of various metals running on ToughMet 3 Condition AT 110, tested according to ASTM G98.

4.1.3 Friction and wear properties of Alloy 25 and ToughMet 3

Tribological test results highlight the excellent friction and wear performance of Alloy 25 and ToughMet 3. They are shown to have exceptionally high sliding wear resistance and the highest galling threshold both among copper alloys and compared to other material families (Figure 3, Table 5 and Table 6).

Table 5 Tribological performance of Alloy 25 and ToughMet 3: Friction values with and without lubrication [24].

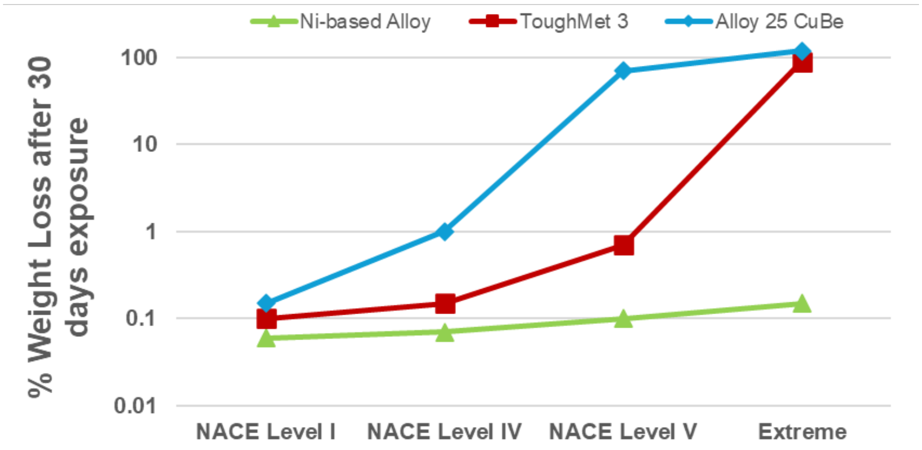
Material	Friction value	
	lubricated	unlubricated
ToughMet 3	0.25	0.63
Alloy 25	0.3	0.4 to 0.5
Carbon	0.1	0.15

Table 6 Tribological performance of ToughMet 3 in comparison with other sliding materials: PV values with and without lubrication [24].

Material	PV values [MPa*(m/s)]	
	lubricated	unlubricated
ToughMet 3	9.63	0.60
Manganese bronze	5.25	-
Aluminium cast bronze	4.38	-
SAE 660 bearing bronze	2.63	-
SAE 841 Sintered bronze	1.75	-
SAE 863 Sintered Iron-Copper	1.23	-
60Cu-40Fe Bronze	1.23	-
High Tin babbit (89%)	1.05	-
Low Tin babbit (10%)	0.63	0.4
Low Tin low Lead (86%) Babbit	-	0.42
Graphite/metallized Bearings	-	0.53
Carbon	-	0.53

4.1.4 Corrosion resistance of Alloy 25 and ToughMet 3

In sliding applications, lubrication is used to reduce friction, and the sliding materials must not be corroded by the lubricants [55]. In certain applications such as biogas, offshore or geothermal energy, the requirements for corrosion resistance are even higher due to the environmental conditions there. Biogas contains hydrogen sulfide and ammonia as well as impurities such as chlorine and siloxanes and is therefore extremely aggressive towards metallic materials. Corrosion damage has also a strong economic impact on offshore structures. This can result in significant damage and even catastrophic structural failure. Important corrosion mechanisms that need to be considered include galvanic corrosion, stress corrosion cracking, microbially induced failure and biofouling [56,57,58,59]. The galvanic series [60] shows that Alloy 25 and ToughMet 3 are quite noble in a seawater atmosphere, which is also due to the formation of protective, tarnishing surface layers. Additionally, the high copper content of about 97 mass-% of Alloy 25 and about 15 mass-% nickel for ToughMet contribute to its antifouling properties [61]. Sour gas according to NACE MR0175 / ISO 15156 and chloride stress corrosion cracking test according to NACE TM0177 / ASTM G49 are good indicators for these applications. As can be seen in Figure 4, Alloy 25 and ToughMet 3 performed very well in these tests [24].



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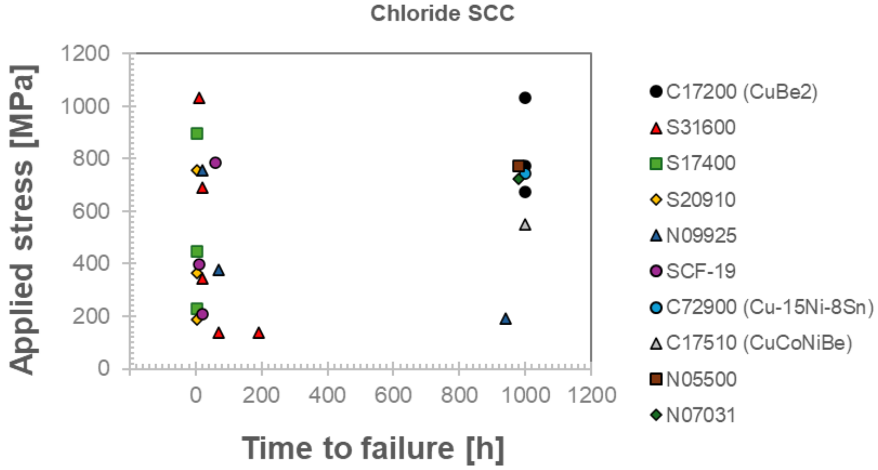
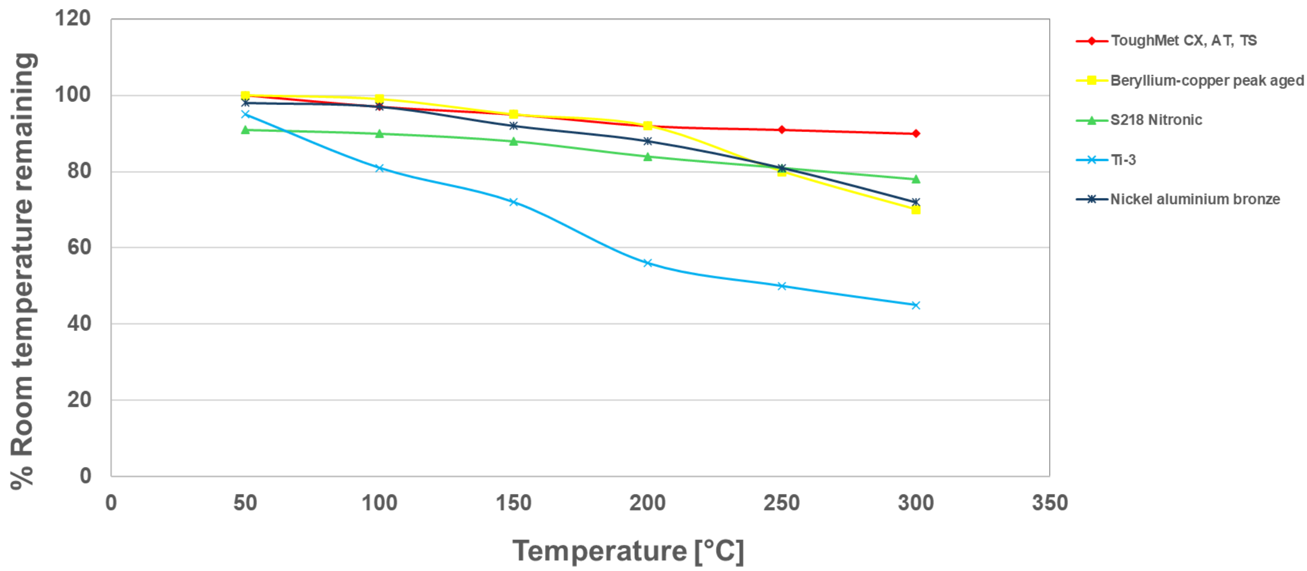


b

Figure 4 Corrosion behavior of different copper alloys: Galvanic series in seawater (a) [51] and results from Mg chloride boiling test (b) [24].

In case of biogas and geothermal energy, corrosion is further triggered having relatively high operation temperatures. In biogas and geothermal energy, corrosion is also driven by relatively high operating temperatures (up to 100 °C for biogas applications and over 150 °C for geothermal energy). The fine and homogeneous microstructures of Alloy 25 and ToughMet 3 are stable at these temperatures, as reflected in the tensile and stress relaxation properties at elevated temperature (Figure 5), and therefore do not provide any nucleation sites for corrosion attacks [24].



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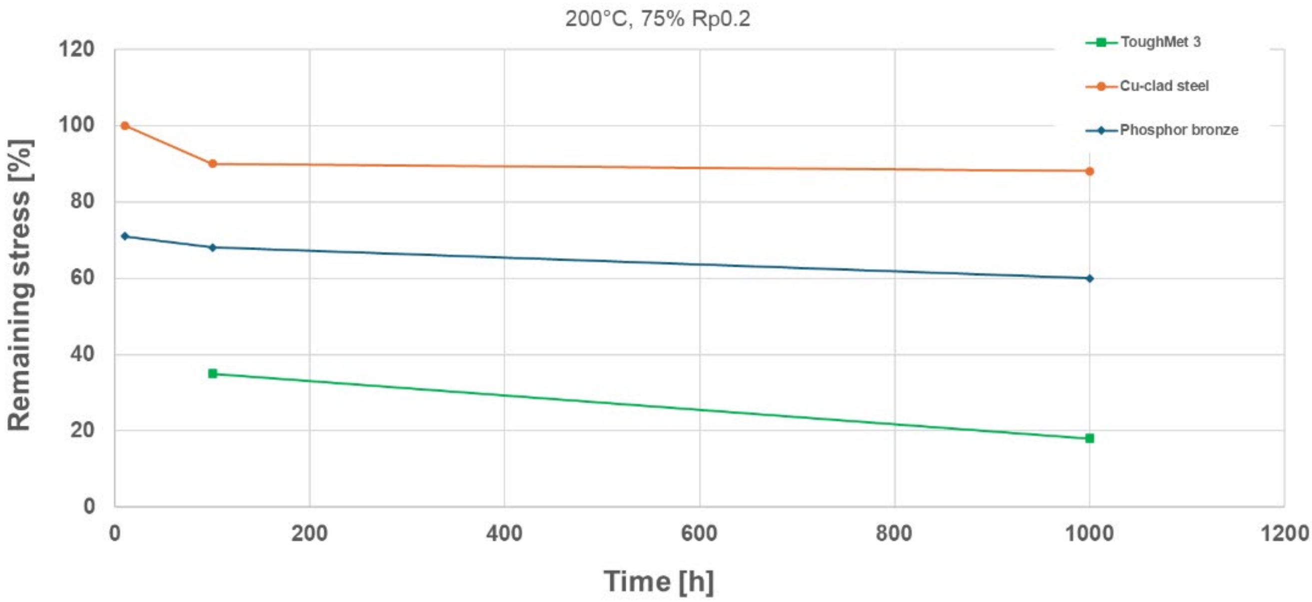


b

Figure 5 Elevated temperature properties of different copper alloys: tensile properties (a) and stress relaxation (b).

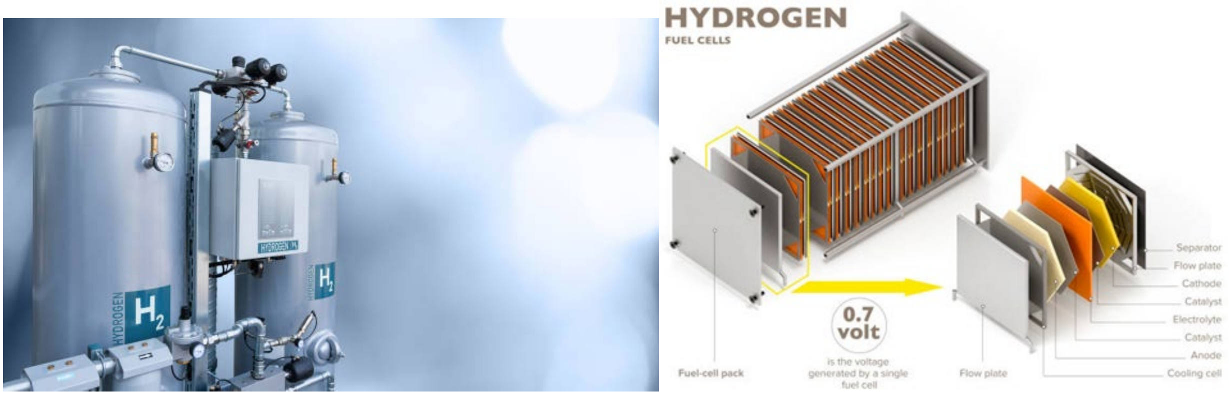
Of course, in all these energy applications, a high level of security and reliability is a fundamental must. In harsh conditions such as wind power, especially offshore, which make maintenance work even more demanding, long maintenance times are also required. Due to the properties considered above, Alloy 25 and ToughMet 3 offer excellent solutions here. Unlike steels, polymers or other copper alloys, these forementioned copper alloys are unique in combining strength and fatigue strength. High wear resistance and low friction as well as excellent corrosion resistance, especially under fluctuating loads and temperatures. If there are additional demands in terms of high thermal conductivity, Alloy 25 is the better choice among these ones while ToughMet 3 provides inferior thermal conductivity but slightly higher corrosion resistance under sour service conditions compared to Alloy 25.

4.2 Clad metals for batteries and hydrogen

4.2.1 Use of batteries and fuel cells for energy storage

Typically, the renewable energies such as solar energy or wind power provide significant fluctuations in power generation, since the amount of energy produced by sources like solar and wind can vary greatly with factors like sunlight and wind speed. For making energy production and energy consumption independent of each other and therefore not to be dependent on these fluctuations, intermediate storage is necessary. The use of batteries and hydrogen are two important ways to store energy [62].

The hydrogen electrolyzer serves to split water (H2O) into its constituent elements, hydrogen (H2) and oxygen (O2), using an electric current. To generate electricity from hydrogen (H2) again, a hydrogen-oxygen fuel cell. In hydrogen fuel cells, hydrogen serves as the fuel and oxygen (O2) as the oxidizer. Chemical energy directly converted into electrical energy [63].



a b

Figure 6 Scheme pictures of a hydrogen electrolyzer (a) and a hydrogen-oxygen fuel cell (b) for energy storage and release.

The main components of the hydrogen electrolyzers (Figure 6a) are electrolytes, electrodes and membranes. A hydrogen fuel cell primarily consists of an anode (negative electrode), a cathode (positive electrode), a proton exchange membrane (electrolyte), gas diffusion layers (GDLs) to distribute gases, bipolar plates to separate individual cells, and a catalyst (usually platinum) on the electrodes, where the chemical reaction occurs to generate electricity (Figure 6b) [63].

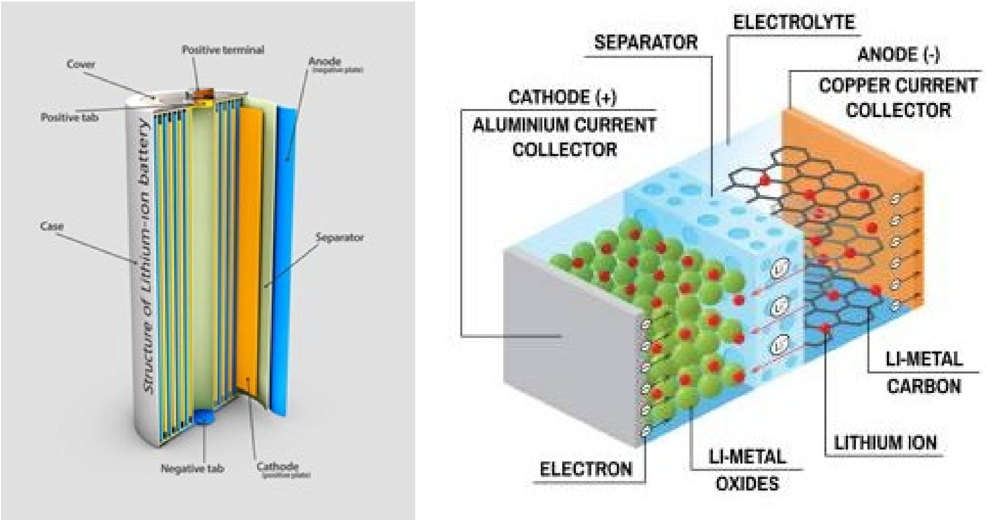


Figure 7 Scheme pictures of a lithium-ion-battery for energy storage and release.

Lithium-ion batteries (Figure 7) have anode, cathode, separator and electrolyte as main components. The current collectors and the terminals are important metallic parts for supplying the current to flow into and out of the battery [64].

4.2.2 Application of clad metals in batteries and fuel cells

Both hydrogen management and batteries offer numerous opportunities to use clad metals. In hydrogen management, electrodes, baffles, bipolar plates, catalysts and gas diffusion layers are prominent examples of benefiting from the advantages of clad metals. The same applies to batteries with electrodes, cell connectors, current collectors, separator walls and housings (Table 7). Clad metals such as stainless-steel-platinum or copper-aluminum is widely used in PEM fuel cells and lithium-ion batteries due to their high conductivity and corrosion resistance.

Table 7 Examples for use of clad metals in hydrogen management and batteries [65-67].

Device	Application	Function	Material combinations (examples)
Electrolyzer / fuel cell	Baffles	To adjust gas flow	
	Bipolar plate	Acting as electrical conductors and gas distributors, connecting adjacent cells (stack), the flow of reactants and products	Ti/graphite Graphite/Ti/steel Ti/steel Nb/steel
	Catalyzer	To control chemical reactions	Pt/steel Pd/steel Ru/steel
	Electrodes (anode/cathode)	Transportation of gaseous species and electrical currency	Cu/Zn Cu/steel Cu/Ni
	Gas diffusion layer	Acting as a pathway for reactant gases, facilitating the removal of heat and water (from electrochemical reactions)	Porous Ni, Ti, Pt or Ru/steel
	Housing	Protecting the components	Al/steel
Batteries	Busbar	Conducting and distributing electrical power	Cu/steel Cu/Al
	Cell connectors	To electrically connect a plurality of battery cells together	Ni/steel/Cu/steel/Ni
	Current collector	To support the electrode materials in conducting the electrical power	Ni/Cu Ni/Cu/Ni
	Housing	Protecting the components	Al/steel/Al
	Separator wall	To protect the battery cells	Al/steel/Al
	Terminal	Electrical contact to connect batteries	Ni/steel/Cu/steel/Ni

4.2.3 Clad metal solutions for fuel cells

The above applications require a combination of very conflicting requirements that a single alloy cannot meet. Only clad metals enable completely new set of properties and much higher performance, and the properties can be provided right there where they are needed placing the right material. This will be explained using the example of a bipolar plate (hydrogen management) and a current collector as well as terminals (batteries). A "bipolar plate" in the context of hydrogen refers to a critical component within a hydrogen fuel cell stack, primarily responsible for conducting electrical current between individual fuel cells, distributing hydrogen and oxygen gases evenly across the cell surface and draining excess water efficiently. Additionally, it provides structural support within the stack. For these reasons, materials for bipolar plates must combine excellent electrical and thermal conductivities, corrosion resistance, good mechanical properties, gas impermeability, and hydrophobicity [63]. Since excellent conductivity is the most important requirement, graphite is used in the original fuel cell. But the use of graphite comes along with some other shortages such as its fragility, porosity, and the time and cost of production [68,69,70,71]. This paves the way for the use of clad metals with a graphite layer, which can be further exploited due to the above-mentioned advantages of good electrical conductivity, and a metal substrate, which contributes high strength, toughness and stiffness, their electrical and thermal conductivities and low gas permeability. Compared to graphite, metals offer higher density, but this disadvantage can be compensated for by their good mechanical properties and allows the production of thin metal plates, thereby reducing the weight and volume of a fuel cell assembly [72].

When used in hydrogen applications, so-called hydrogen embrittlement is always mentioned, which many higher-strength materials are prone to [73]. Recent research has shown that Alloy 25 has excellent durability in hydrogen environments. This, in conjunction with other high-performance properties of beryllium copper alloys, makes Alloy 25 an excellent solution for hydrogen applications [23].

4.2.4 Clad metal solutions for batteries

For battery terminals, it is often necessary to connect copper and aluminum. Because these elements tend to form intermetallic compounds that degrade electrical conductivity and make the interface brittle, the bonding processes can be very demanding. Dovetail overcomes this challenge. It combines a zigzag interface to increase the bonding area and a roll bonding process to suppress the formation of intermetallic compounds. This maximizes adhesive strength and electrical conductivity [40].

A current collector is a thin layer of metal that carries electric current in a battery. They are an important component of batteries and therefore must fulfill high electrical and thermal conductivity, good chemical and electrochemical stability, high mechanical strength, compatibility and strong bonding with the electrode material and lightweight [67]. These contrasting properties again require the use of clad metal. This is the only way to combine all requirements in one and find a solution that requires minimal use of materials. A copper layer provides the desired conductivity, while a nickel layer contributes to corrosion resistance, mechanical strength and surface properties required joinability with the terminal material [74]. Niobium is another important material in batteries. It is used as a cladding layer for cathodes to reduce charging time and improve longevity of lithium-ion batteries [75].

4.3 Thermal management in energy applications
4.3.1 Material requirements

Energy applications and therefore also renewable energies generate a lot of heat that must be dissipated. This not only serves to protect the materials in these applications, but maintaining temperatures within a certain operating range is essential to ensure functionality, reliability and security of the energy systems. The typical temperature range for operation of fuel cells is from 20 °C to 80 °C (low temperature technology), 100 °C to 130 °C (medium temperature technology) or 130 °C to 200 °C (high temperature technology), for instance. Ceramic fuels cells (SOFC) even work at temperatures between 450°C and 1000°C [76]. Lithium-ion batteries can operate between −20°C and 60°C. Their optimal operating temperature, however, is between 15°C and 35°C [77]. Fuel cells and batteries are just two examples that illustrate the importance of thermal management for renewable energy applications. Consequently, the main function of these components is to remove heat from the system being cooled, therefore demanding high thermal conductivity and heat capacity, but secondary requirements also include corrosion resistance, strength and stiffness.

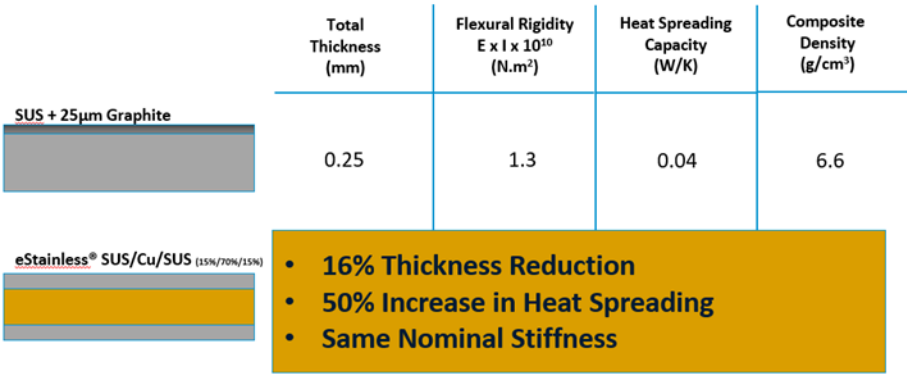


Figure 8 Benefits of clad metals for thermal management.

4.3.2 Application of clad metals

Here too, clad metals are an optimal solution. Figure 8 shows the example of eStainless [41] and compares it to a stainless steel (SUS) substrate with a layer of graphite on it (called reference). In this example, the system is changed to a three-layer SUS/Cu/SUS system, thereby achieving 50% higher heat spread with the same nominal stiffness as the reference and yet smaller thickness. Therefore, clad metals can be used to adapt the material to the specific thermal engineering task, thus providing efficient customized solutions.

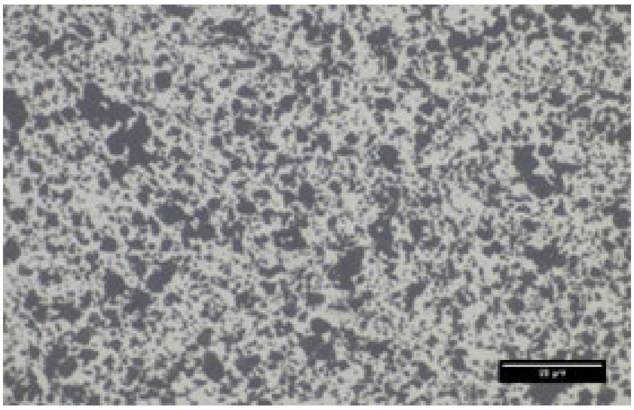


Figure 9 Typical microstructures of hypereutectic Al-Si AyontEX, aluminum matrix (light) and elementary silicon (dark)

4.3.3 Application of aluminum matrix composites

Another material group that is attractive for thermal management applications is AyontEX metal matrix composites. In some ways they function similarly to clad metals. This means that in this case too, a second component is used to reduce thermal expansion and increase stiffness, while at the same time benefiting from a metal with high thermal conductivity as a further component [78]. Unlike Clad Metals, the second component is not applied as a layer, but is distributed evenly across the entire metal matrix in the form of particles. A main advantage of aluminum matrix composites such as AyontEX (Figure 9) therefore is the spherical shape of the reinforcement particles and their homogeneous distribution throughout the material, allowing isotropic properties. Therefore, the thermal expansion does not depend significantly on the direction in the material product [79].

4.4 Metals for fusion reactors and new generation of fission reactors
4.4.1 Brief history of use of nuclear fusion for energy production

The idea of using nuclear fusion to generate energy goes back to Arthur Eddington, a British astrophysicist who first published the theory in 1926 that stars produce energy by fusing hydrogen into helium [80]. From a renewable energy perspective, this idea is a very attractive option as it could use abundant fuel, there would be no carbon emissions and no nuclear waste, as would be the case with energy production from conventional nuclear energy. After researchers began studying ways to replicate nuclear fusion on Earth in the 1950s, it soon became clear that this would be a major challenge. Therefore, in 1973, European countries came together to work together on this issue, the most recent result of which is ITER (International Thermonuclear Experimental Reactor, Figure 10) [81]. The practical use of nuclear fusion is a challenge for many reasons: extreme temperatures (the fusion process requires temperatures of over 100 million degrees Celsius), intense pressure (extreme pressure is needed to force the nuclei to fuse) and confinement of the plasma (it must be held stable and confined long enough to generate a net power gain).

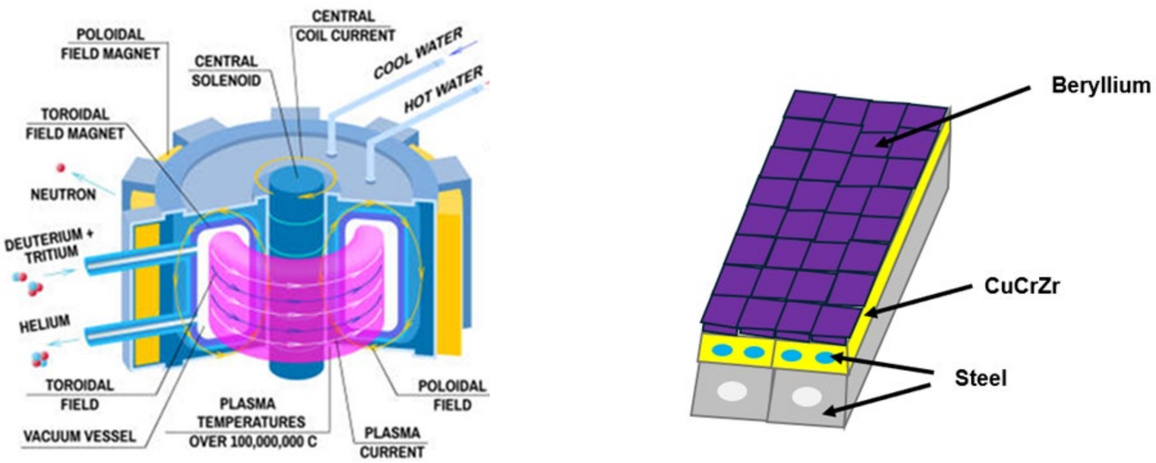


Figure 10 Scheme picture of nuclear fusion reactor ITER and scheme picture of a blanket module of the first wall [81-83].

4.4.2 Material requirements

This means that the first wall (surface of the inner wall of a fusion reactor), which is directly influenced by the plasma and its components, must meet enormous requirements [82,83]:

- Very high temperatures - up to 1,000 °C
- It is also continuously bombarded by ions from the plasma and must be able to withstand an environment with high-energy neutrons (neutron absorption in the wall must be kept low, no degradation of the material properties, no activation)
- High mechanical strength
- Good hydrogen compatibility (low absorption, low permeability and resistance to hydrogen embrittlement)

4.4.3 Beryllium for nuclear fusion

All these requirements are perfectly met by using beryllium for the first wall. Beryllium is known for its excellent core properties, high strength, high melting point and high thermal conductivity and offers good hydrogen compatibility [8]. Therefore, beryllium has long been chosen as the main material for the components exposed to strong plasma heat. At the end of this chapter, it must also be mentioned that in 2023 the ITER organization decided to modify the armor material planned for the first wall of the ITER ceiling with tungsten material [84]. However, the fundamental suitability and relevance of beryllium for this purpose is not affected by this decision [85].

4.4.4 Molten salt reactors

Molten salt-cooled high-temperature reactors are a promising new concept in nuclear fission to reduce the carbon footprint of electricity generation. For molten salt nuclear reactors, Flibe, a mixture of beryllium fluoride and lithium fluoride, is an ideal heat transfer fluid. It provides very high thermal capacity, chemical stability, and desirable neutron moderating characteristics. These characteristics make Flibe an outstanding choice as a coolant for the Kairos Power's Fluoride Salt-Cooled High-Temperature Reactor (KP-FHR) [86].

4.5 Sensors and switches for safety in energy applications
4.5.1 Function of sensors and switches in renewable energy

With renewable energy, many variables and functions need to be managed. This can include temperatures, pressure, humidity, gas composition, position and movement. When dealing with solar power, for example, it is important to be aware of devices becoming too hot. They are also used to monitor liquid temperature in various applications. Other technologies such as hydrogen or batteries also have their temperature controlled to maximize efficiency and ensure safety (see also 3.3). Sensors are used to monitor these variables and switches are used to control them.

4.5.2 Material requirements

To ensure their function as well as reliability and longevity, these devices must meet a variety of requirements that depend heavily on the specific application [87,88]:

- Very precise thermal expansion: It has already been explained that temperature windows play a crucial role in renewable energy processes. In many cases, thermal sensors and switches respond to temperature changes through thermal expansion, which can be linear (monometals) or can result in bending (clad metals). In both cases, the change in thermal expansion must occur very precisely and with high reproducibility.
- Stiffness: Sudden events or vibrations lead to small and therefore typically elastic deformations. Since these deformations can impair the function of sensors and switches, high rigidity and thus material stiffness is an important measure to suppress them.
- Non-magnetic properties are required for situations where magnetic interference could be problematic, e.g. with mechanical switches or capacitive sensors.
- Compatibility with different environments: Biogas, geothermal energy and offshore/subsea energy applications are just three examples where the materials must perform in harsh environmental conditions. Under these circumstances, good corrosion resistance is required. This includes many different media that can occur in different applications.
- Sensors and switches for use in gaseous environments must be compatible with the process gas composition present in the application. Hydrogen is an example. Materials for hydrogen applications must be inert to hydrogen and offer a defined hydrogen permeability. This also means that the sensor material should respond selectively to these conditions. In particular, the gas composition which is present in the application plays an important role for the material selection.
- The above properties are required across the entire application temperature range. The smaller

the temperature-dependent variation in the desired properties, the better. In addition, no material degradation is desired over the entire service life.
- Further requirements for functional optimization of sensors and switches are short response time, reliability and longevity.

4.5.3 Copper-beryllium and pure beryllium

To meet these requirements, there are a variety of material solutions. To ensure non-magnetic behavior, non-ferrous metals such as copper alloys are a good choice. These include copper-beryllium alloys, e.g. Alloy 25, which combines many advantageous properties: non-magnetic (diamagnetic) properties, high strength and stiffness, good corrosion resistance and hydrogen compatibility, high thermal stability, low mitigation of physical properties at temperatures up to 300°C and very good reproducibility of these physical properties [34]. These properties are due to a combination of very small windows of chemical compositions and a manufacturing process that involves the production of very fine and homogeneous powders before further hot and cold forming and heat treatment.

When even greater precision is required, using pure beryllium is a good choice. Its outstanding performance in thermomechanical sensors and switches is due to extremely high stiffness and relatively low thermal expansion that remain constant over a wide temperature range [20].

4.5.4 High temperature materials

For even higher temperature or corrosion requirements than can be met with beryllium-copper, other metals such as nickel or tantalum are also available. These metals can be used in even harsher corrosive environments such as acids and at temperatures of 350°C (nickel Alloy 360) respectively 500°C (tantalum alloy ULTRA 76 Plus) or even higher. Such metals can also be used for more specific tasks in sensors and control systems for renewable energy. As an example, reports on the application of tantalum base materials in optical metal-hydride hydrogen sensors. Their working principle is based on the fact, that the optical properties change when metal hydrides partly hydrogenate when they are exposed to a hydrogen atmosphere [89].

Oxides are another group of materials that are attractive for the development of integrated chemical and physical sensors. Thus, Chen et al. report Al_2O_3 based moisture sensors [90] while Eranna et al. describe the efforts to develop of miniaturized gas-sensing devices made of oxide materials [91].

4.5.5 Clad materials

Clad metals can also be used for sensors and switches. They can be even better adapted to specific conditions such as stiffness or thermal expansion. Very contrasting properties such as thermal conductivity and stiffness can be combined using clad metals [42]. By combining two metals with very different thermal expansion, for example steel and copper or nickel and copper, as a bimetal, a temperature switch is created that opens or closes an electrical circuit in response to a measured temperature. Bimetals are used to keep batteries and fuel cells within a specific temperature range to optimize high efficiency and prevent malfunctions or even more serious failures.

5. CONCLUSIONS

Several examples were shown highlighting the use of high-performance materials in renewable energy applications. In some cases, such as plain bearings in wind energy, these materials like Alloy 25 or ToughMet 3 just help to extend the service life. In other cases, high-performance materials are essential for the sufficient efficiency of renewable energy technologies or even for enabling these new technologies. This publication gave several examples of the latter: CuBe2 and ToughMet 3 with high temperature stability and corrosion resistance for biogas and geothermal energy, clad metals for batteries and hydrogen or beryllium for nuclear fusion reactors, to name a few. Small devices such as sensors, switches or catalytic converters can be of great importance for the reliability and safety of these technologies. Numerous high-performance materials can be used for sensors and switches, including beryllium-copper (Alloy 25), nickel (Alloy 360), tantalum (ULTRA 76 Plus alloy), clad metals and technical ceramics. The future of renewable energies lies in a sensible mix of different technologies and as diverse as the technologies are, the variety of materials for them is just as diverse, as well. Sophisticated material technologies such as composite materials or clad metals make it possible to respond to as yet unknown future requirements.

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