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Development of tungsten armor and bonding to copper for plasma-interactive components

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Abstract

For the highest sputtering threshold of all possible candidates, tungsten will be the most likely armor material in highly loaded plasma-interactive components of commercially relevant fusion reactors. The development of new materials, as well as joining and coating techniques are needed to find the best balance in plasma compatibility, lifetime, reliability, neutron irradiation resistance, and safety. Further important issues for selection are availability, costs of machining and production, etc. Tungsten doped with lanthanum oxide is a commercially available W grade for electrodes, designed for low electron work function, higher recrystallization temperature, reduced secondary grain growth, and machinability at relatively low costs. W–Re and related tungsten base alloys are preferred for application at high temperatures, when high strength, high thermal shock and recrystallization resistance are required. Due to the high costs and limited global availability of Re, however, the amount of such alloys in a commercial reactor should be kept low. Newly measured material properties up to high temperatures are presented for lanthanated and W–Re alloys, and the impact on fusion application is discussed. Recently developed coatings of chemical vapor deposited tungsten (CVD-W) on copper substrates have proven to be resistant to repeated thermal and shock loading. Layers of more than 5 mm, as required for the International Thermonuclear Experimental Reactor (ITER), became available. Vacuum plasma sprayed tungsten (VPS-W) in particular is attractive for its lower costs, and the potential of in situ repair. However, the advantage of sacrificial plasma-interactive tungsten coatings in long-term fusion devices has yet to be demonstrated. A durable and reliable joining of bulk tungsten to copper is needed to achieve an acceptable component lifetime in a fusion environment. The material properties of the copper alloys proposed for ITER, and their impact on the quality of bonding to tungsten is discussed. Future materials R&D should concern issues such as plasma compatibility, and above all neutron irradiation damage of promising tungsten–copper joints.

1. Introduction: Properties and use of tungsten

Tungsten, chemical symbol W, solidifies in a body-centered-cubic crystal lattice, and with ~0.006 wt% crustal abundance is almost as frequent as Ni or Cu. Tungsten was discovered more than 200 years ago, for larger slag formation in the production of tin. The principal ores $FeWO_4$, $MnWO_4$ and $CaWO_4$ are found in Southeast Asia, North America and Austria.

Due to the highest melting point, 3410°C, and lowest vapor pressure, 1.3×10^{-7} Pa (at T_{melt}), of all alloyed and unalloyed metals, tungsten and its alloys are well suited for all kinds of high-temperature/high-vacuum application. For its good erosion resistance there is wide use as contact material in switches, as well as filament or electrode material in lighting, welding and spark erosion; for the low thermal expansion it is an excellent material for vacuum-tight glass seals. Further, tungsten is used in heating elements for its high strength and geometrical stability at elevated temperatures, and in thermocouples up to 2000°C when alloyed with rhenium. For its high density and high atomic number ("high-Z") there is considerable use in medical X-ray,

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but also in nuclear components, including shielding. Finally, there is widespread use of tungsten-carbide in wear resistant parts and hard metals.

The actual and intended use of W as plasma facing armor so far was based on the experience and materials database from existing commercial application, rather than to stimulate the development of new alloys, see Table 1. Exceptions so far are tungsten coatings of considerable thickness, in particular chemical vapor deposited tungsten (CVD-W) and vacuum plasma sprayed tungsten (VPS-W)-see there.

A comprehensive discussion of tungsten material properties, including a review of the literature with technical and commercial relevance for nuclear/high-temperature application, is available from the US Space Program [1,2]. A universal collection of all interesting properties for application is found in the Plansee product documentation [3]. Although the use of refractory alloys in fusion reactors in general was considered several decades ago, see e.g. [4], experimental results on plasma performance and surface interaction gathered from operation with high-Z armor in different fusion devices have been reported only recently [5]. Interesting to note that, concerning the exposure of tungsten to a (fusion) plasma, five years ago almost no experimental results were available. Since substantial efforts to develop and characterize new tungsten alloys for fusion were triggered towards the end of the last decade, at the ICFRM-4 1989 in Kyoto only three papers on tungsten were published [6–8]. Six years later, 1995 at the ICFRM-7 in Obninsk, however, that number increased to fifteen – find some of these in [9–15]. 1997 at the ICFRM-8 in Sendai more than 20 papers with tungsten relevance were presented – find some of these in [16–28]. For high-Z tungsten armor, this indeed is an outstanding gain in popularity within the fusion community.

In near-term fusion machines a wider use of tungsten armor is foreseen. In the International Thermonuclear Experimental Reactor (ITER) parts of the baffle, as well as the upper regions of the inner and outer vertical targets of the divertor will be armored with tungsten. For the very high heat fluxes the bottom region of the divertor will be covered with CFC (carbon-fiber-reinforced-carbon) [30–33]. One of the long-term goals of ITER is to armor even these high heat flux regions with tungsten.

For their fairly high thermal conductivity and a very high melting temperature – both helpful to improve the passive safety in case of off-normal and disruptive plasma events, as well as the good match in thermal expansion, W–(5)Re alloys were proposed for the heat-sink of a carbon armored divertor [37–42], too.

This paper focuses on the technological development of tungsten alloys, and joining to copper heat-sinks. Properties of the commercially available tungsten alloys W–1% La_2O_3 and W–5Re, newly measured up to high temperatures, are presented. For the heat-sink of tungsten armor, the classical copper alloys DS–Cu and CuCrZr are compared to CFR–Cu, a composite material still under development.

2. Plasma-surface interaction and armor lifetime

An effective impurity control and ash removal requires that plasma-interactive components intersect the path of particles in edge plasma regions. For that there is either a "limiter" pointing deeper into the plasma than the first wall, or the outer plasma layers are diverted out of their poloidal symmetry to hit the "divertor", see e.g. [32–37]. When slowed down and neutralized, plasma particles deposit a very high portion of their energy to the plasma facing surface of the armor material, making necessary an efficient heat removal to the coolant, and leading to armor erosion. In addition plasma instabilities and the discontinuous energy deposition will cause severe thermal shocks and fatigue loading to the armor, and such reduce the armor and component lifetime. A useful approach to predict that lifetime has proven to be a joint effort of physicists, experimentalists and materials engineers [9,38].

The material and physics issues related to the exposure of matter to plasma are critical for the overall plasma performance, see e.g. [5,32]. Due to its high-Z, a small content of W would very efficiently cool a fusion plasma by radiation losses, and prevent ignition [39,40]. The energy of the edge plasma should be kept below ~200 eV, which is the threshold for physical sputtering of W by deuterium, to avoid massive erosion. As reported recently, a suitable control of high-Z impurity migration and accumulation in the main plasma seems feasible [5].

Contrary to thermomechanical fatigue [41], the erosion resistance in W–Re alloys drops as the Re-content is increased [11]. Alloying tungsten with Re or doping with La_2O_3 are expected to have a different impact on irradiation damage, but also on the impurity control and content in the plasma. Future materials R&D should address these issues in more detail.

3. Neutron irradiation of tungsten

In case the plasma is operated with deuterium and tritium, in-vessel components will be exposed to considerable neutron irradiation. Due to the high density, high-Z and relatively high neutron capture of tungsten (see Table 1), transmutation of the stable and terrestrial tungsten isotopes into a variety of radioactive (and also a few stable) nuclides will occur. That mix of transmutation products will mainly consist of Re, W, Os, Ta, but

Table 1
Physical and mechanical properties of some high-Z and heat-sink materials [a]

	W	W–1%La$_2$O$_3$	W–5%Re	W–30Cu ~50 vol% W	W–Ni–Fe ~95 wt% W	W–Ni–Cu ~95 wt% W	Ta	OF-Cu	CuCrZr & DS–Cu	CFR-Cu [b]
Density at RT, g/cm^3	19.3	18.9	19.4	14.0	18.0	18.0	16.6	8.9	8.9	5.3
Thermal expans. coeff. at RT, 10^{-6}/K	4.5	4.7	4.5	11.5	5.5	5.2	6.3	16.6	16.8	5.0 $\parallel$, 22.0 $\perp$
Thermal cond. at RT/1000°C, W/mK	145/113	120/98	70/83	300/~220	83/-	108/-	57/61	400/	340/	>200 $\parallel$, 100 $\perp$
Elastic modulus at RT, GPa	410	~410	400	218	380	350	186	85	135	150
Ultimate strength at RT, MPa	1000	900	1100	520	850	680	300	210	~440	770 $\parallel$, 50 $\perp$
Poisson ratio	0.28	(0.3)	0.3	0.3	~0.3	~0.3	~0.3	0.33	0.34	(0.3)
Tensile elongation at RT/1000°C, %	<0.4/25–30	<0.4/25–30	~1/13	~3/	16/	3/	30/	~50/	~25/	
Specific heat at RT, J/gK	0.14	0.14	0.14	0.24	0.19	0.18	0.14	0.39	0.39	0.46
DBTT, °C	100 ~ 400	~ as W	50 ~ 200	(<RT)	(<RT)	(<RT)	−200°C			
Recrystallization temperature, °C	1150–1350	1250–1700	>1500				900–1400			
Melting point, °C	3410	~ as W	~3300	1080(Cu)	~1400	~1050	3000	1080	(1080)	(1080)
Max. temperature of application	$\leqslant$ 3410	~ as W	($\leqslant$ 3300)	$<T_{\mathrm{melt}}$	$\ll T_{\mathrm{melt}}$	$\ll T_{\mathrm{melt}}$		$<T_{\mathrm{melt}}$	$\ll T_{\mathrm{melt}}$	$<T_{\mathrm{melt}}$
Vapor pressure at 2000°C, Pa	1.3×10^{-7}	> as W	$\geqslant$ as W	(Cu)	(Ni)	(Cu)	2.7×10^{-6}			
Atomic number	74	(74)	(74)	(49)	(67)	(68)	73	29		
Atomic weight	183.8	(183.)	(184)	(117)	(166)	(167)	180.9	63.5		
Cross section for thermal neutrons, b	18.5	(18.)	(21.8)	(10.4)	(16.3)	(16.5)	22	3.8		
Estimated neutron leakage (W = 100%)	1.0	~1.0	~1.0	0.5	0.8	0.85	0.95			
Estimated costs: (as of late 1997)										
Material, US$/kg	~150	W, +20%	~400							
Machining	High	Low	Medium	Low	Low	Low	Low ?			
Joining – possible:										
Brazing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Welding	No (?)	No	No ?	No	No	No	Yes	Yes	Yes/No	No

[a] Typical values, high-Z materials also identified as potential candidates for neutron spallation targets (solids only) [42,43].

[b] Carbon-fiber-reinforced copper, composition fiber:copper $\approx$ 50:50 vol%; approximate property values given here.

also Hf, Ir, Pt, Au and Hg, some of which due to their instability will decay further [2,21,44–54]. Shortly after terminating thermonuclear plasma operation the decay power, responsible for the afterheat, will be much higher in irradiated tungsten than in most of the other in-vessel materials. This is a disadvantage for the passive safety. On the other hand, after approximately one month that decay power drops for several orders of magnitude, which is an obvious advantage for long-term storage and recycling [44]. For the next ~1000 years even the copper in the heat-sink is going to produce more afterheat due to the long half-life of the generated nuclides of Ni, Co and Fe [45]. Basically this is also true for Re and La. Therefore water cooling of n-irradiated tungsten material not necessarily has to be continued beyond the first month after plasma shutdown.

Further, the swelling of tungsten at higher dose rates is strongly reduced for all irradiation temperatures when alloyed with rhenium [2,43,46]. The DBTT of W–Re increases when irradiated at lower temperatures [54]. However, as known from Mo–Re alloys, the DBTT is expected to remain practically unchanged if the irradiation takes place (well) above the DBTT [21,55]. First results of W–5Re and W–1%La_2O_3 from the last ITER neutron irradiation campaign are becoming available soon, hopefully answering some of the relevant questions here.

If Re is present in the initial alloy, there will be transmutation and substantial burn-up of Re as well [44–51]. In case the neutron spectrum is well known and the plasma is operated continuously, and if to some extent the generation of Re from W burn-up is compensated by the burn-up of Re [51], the rhenium content in a W–Re-base alloy can be kept rather constant. Therefore, to reduce the degradation of material properties caused by burn-up, there is good reason for alloying W with a few percent of Re. It is to be noted here that the natural "terrestrial" Re isotopes and the generated nuclides are not identical. This might influence the principal interaction with neutrons, but not necessarily the metallurgical and mechanical properties.

The role of La_2O_3 under neutron irradiation was not studied yet, nor can it be estimated easily, because all former n-irradiation of tungsten alloys (see e.g. [2] for nuclear space power reactors, and [54] for neutron spallation considerations) focused on pure or Re-alloyed tungsten, rather than dispersion strengthened W–La_2O_3 or W–ThO_2. Only recently in the EU Fusion Programme specimens for mechanical and thermophysical characterization of these materials were subjected to neutron irradiation. Results of the post-irradiation characterization are to be reported soon [55].

Neutron irradiation of tungsten over a longer period, e.g. exposure to a burning plasma over one year, will lead to substantial burnup of W in a thin surface layer [48–51], making the response to a higher fluence less predictable. Due to a strong self-shielding of W (and Re), other armor regions than the thin surface layer directly facing the burning plasma, and even more so the heat-sink and structural parts of in-vessel components behind tungsten, will be exposed to a softer neutron spectrum.

For components to be armored with tungsten, today there is no in-depth agreement on the expected n-spectrum. The quantity of 14 MeV neutrons – their absolute amount as well as relative to the rest of the neutron spectrum – and the degree of spectrum softening as a consequence of the location in the component/machine, cannot be predicted with very high accuracy. Another difficulty associated with n-irradiation is that the neutron spectrum from a fusion plasma cannot be fully simulated in a fission reactor, complicating the interpretation of irradiation results. In addition there are strong resonances in the cross section for epithermal (1 ~ 1000 eV) neutrons [48], making all predictions of irradiation damage less certain.

Newly evaluated neutron cross section and transmutation calculations for W have been reported [47–52]. However, contrary to carbon armor, as well as heat-sink and structural materials of in-vessel components, for the commercially available tungsten alloys there is still a distinct lack of experimental fusion-relevant irradiation data. A universal answer to the impact of neutron irradiation presently is not possible. If the fusion community continues to consider a wider use of tungsten armor in future fusion reactors, neutron irradiation of all high-Z candidate materials – preferably already joined to the heat-sink, at all temperatures and fluences of interest becomes indispensable.

4. Ductility, recrystallization and machining of tungsten

Due to the high melting temperature of tungsten and its alloying materials, the typical route of production is based on powder-metallurgical sintering, taking place at 0.5–0.9 T_s (the solidification temperature in K). Besides fabrication, the raw materials, the alloying elements and dopants/impurities, pre- and post-treatment, and the final shape/geometry have a strong impact on the achieved properties of tungsten.

When subjected to frequent temperature changes, the ductility becomes a major issue. Crossing the DBTT (ductile to brittle transition temperature) under mechanical load should be avoided in any material. Due to its body-centered-cubic lattice, at RT tungsten is of brittle and refractory nature. The use as structural material in particular should be limited to operating temperatures above the DBTT. In the case of recrystallized tungsten-rhenium alloys, the DBTT is ~RT for 26 wt%Re (W–26Re), linearly increasing up to ~350°C when reducing the rhenium content down to 0% (i.e. pure tungsten) [41]. Hot working is strongly desirable before assembly or use of the final product; such even the DBTT of W–5Re can be reduced down to ~RT if enough cold/hot working is performed after sintering, see Table 1.

To achieve better mechanical properties, and also to eliminate the remaining porosity, forging or rolling can be performed after sintering. After extensive cold/hot mechanical working the texture is favorable due to the higher amount of grain boundaries, but also is highly anisotropic, which can only in part be compensated by heat treatment above the recrystallization temperature. To avoid massive distortion of the final component at least one heat treatment has to take place before assembly to allow some stress relieve. When heated above the recrystallization temperature, the structure of tungsten is altered due to grain growth which reduces strength and hardness, and causes brittleness. The temperature of recrystallization depends mainly on the deformation history and the chemical purity. Experience shows that incomplete recrystallization often proves to be of better use to achieve the desired balance in material properties. If the operating temperature is well known, controlled recrystallization during application is allowed as well [1–4,16–18,41,56–60].

Although La_2O_3 additions to tungsten do not reduce the DBTT initially, the material becomes machinable at RT, and thus at lower cost. Also, the temperature of recrystallization rises by 100–350 K [56–58], see Table 1. However, by mechanical alloying it is even possible to improve the ductility. The reason is a thorough microscopic distribution of the oxide or carbide particles at grain boundaries. Secondary grain growth (grain boundary migration) at higher temperatures is suppressed [17], slowing down recrystallization, i.e. increasing the recrystallization temperature. Also low-temperature toughness is improved, and the DBTT drops, too. The drawbacks of mechanical alloying in general, besides the considerably higher costs of fabrication are the increased hardness causing problems for hot-working, a lower thermal conductivity than pure W, and compared to regular powder-metallurgical production (almost) no improvement in thermal shock resistance.

5. Technical tungsten qualities for plasma-interactive components

In the following the technical tungsten qualities presently discussed as armor for plasma-interactive components of near-future fusion machines are presented. Within the ITER Engineering Design Activities [34] the material properties for some of the following tungsten alloys have been collected, and are now available for design considerations [61].

5.1. W–1wt%La_2O_3

The addition of La_2O_3 to tungsten improves the grain boundary strength at ambient and elevated temperatures, resulting in a remarkable improvement of the thermal shock and creep resistance, in the machinability and hot tensile strength [56].

W–1%La_2O_3 has a higher recrystallization temperature as well as higher thermal strength, and only a slightly reduced thermal conductivity compared to pure tungsten. This material was developed to replace thoriated tungsten for high temperature application, where a good erosion resistance and low electron work function are needed [3]. Without special pre-treatment such as mechanical alloying, the addition of the insoluble La_2O_3 to tungsten reduces the DBTT only insignificantly, still complicating an application at moderate temperatures. However, the machinability at room temperature is good (i.e. inexpensive). This is attributable to the fact that during deformation and machining no micro-cracks are formed in the vicinity of the dispersed La_2O_3 particles, as they deform together with the W-matrix [56]. Because of easy low-temperature machining the price for parts made of lanthanated tungsten will be even lower than for parts of pure W, see Tables 1 and 2.

For the well balanced material properties, experience in other areas of application, lower costs for the raw materials and machining, as well as absence of a high neutron fluence in the first generation to the ITER divertor, W–1%La_2O_3 was selected as reference high-Z armor for the divertor and baffle of ITER [34].

5.2. W–5wt%Re

Tungsten has a high solid solubility for Re; at elevated temperatures more than 30 wt% of rhenium can be substitutionally built in the tungsten lattice. Rhenium is a rare element, its price is comparable to pure gold. Rhenium additions to tungsten improve the creep strength and recrystallization resistance, this was reported before 1960 [57,58]. However, the primary reason for alloying with Re is to take advantage of the improved ductility even at lower temperatures. W–5wt%Re, a single phase material, still has a fairly high thermal conductivity, compared to rhenium-free tungsten alloys an excellent thermal shock/fatigue and recrystallization resistance, and a high strength and good braze – as well as some weld-ability, see Tables 1 and 3. The manufacture and machinability of W–5Re even at room temperature is adequate for the size and shape of high heat flux armor in plasma-interactive components.

Limited data exist concerning irradiation damage of W–Re alloys for structural application [2,54]. The swelling of tungsten at higher dose rates is strongly reduced for all irradiation temperatures when alloyed with

Table 2
Thermophysical and mechanical properties of sintered W–1wt%La_2O_3 [a]

Temperature (°C)	Thermal conductiv. (W/mK)	Specific heat (J/gK)	Thermal diffusivity (10^{-6} m^2/s)	Therm. exp. coefficient (10^{-6}/K)	Yield strength (0.2%) (MPa)		Tensile strength (MPa)		Tensile elongation (%)	
					ϕ 25 mm	ϕ 40 mm	ϕ 25 mm	ϕ 40 mm	ϕ 25 mm	ϕ 40 mm
RT		0.1308	0.464							
100	120.4	0.1393	0.460	4.83						
200	117.8	0.1426	0.440	4.88	–	–	–	755	–	–
300	113.6	0.1437	0.418	4.93						
400	109.0	0.1453	0.401	4.97						
480					–	430	–	467	–	25.0
500	105.8	0.1459	0.388	5.03						
600	102.9	0.1475	0.374	5.06						
700	102.8	0.1486	0.371	5.10						
800	100.3	0.1502	0.359	5.14						
900	100.7	0.1516	0.357	5.21						
1000	98.5	0.1525	0.348	5.28	362	337	373	354	27.5	15.0
1100	96.2	0.1534	0.339	5.32						
1200	94.8	0.1549	0.332	5.37	296		299		21.9	
1250						292		297		16.0
1300	94.4	0.1555	0.329	5.41						
1400	94.2	0.1548	0.324	5.45	236		237		23.2	
1500			0.318	5.50		93		136		65.0
1600			0.307		158		164		37.8	
1800					59	34	93	90	61.2	83.0
2000					48		71		61.0	

[a] rod ϕ 25 or 40 mm, swaged with ~85% hot-work, stress relieved, typical values.

Table 3
Thermophysical and mechanical properties of sintered W–5 wt%Re

Temperature (°C)	Thermal conductivity (W/mK)	Specific heat (J/gK)	Thermal diffusivity (10^{-6} m^2/s)	Therm. exp. coefficient (10^{-6}/K)	Emissivity			Yield strength (0.2%) (MPa)		Tensile strength (MPa)		Tensile elongation (%)	
					Sandblasted	As received (1st/later measurement)	Polished	Longitudinal	Transversal	Longitudinal	Transversal	Longitudinal	Transversal
RT			0.243					–	–	1086	240	–	–
100	68.7	0.139	0.260	4.78									
200	70.7	0.141	0.264	4.86									
300	70.8	0.143	0.261	4.92									
400	74.9	0.145	0.273	4.85									
500	79.4	0.147	0.286	4.86				902	–	963	606	10.8	–
600	80.4	0.149	0.287	4.87									
700	80.9	0.151	0.285	4.92	0.48/0.35	0.20/0.13	0.11/0.10	832	–	880	632	12.9	–
800	82.5	0.152	0.287	4.94	0.46/0.36	0.19/0.14	0.11/0.10						
900	82.7	0.154	0.285	5.02	0.47/0.37	0.19/0.16	0.12/0.11	772	656	808	755	12.7	3.8
1000	82.7	0.156	0.281	5.06	0.46/0.38	0.19/0.15	0.13/0.13						
1100	84.3	0.158	0.284	5.11	0.44/0.39	0.20/0.20	0.14/0.14	738	598	758	633	14.0	0.4
1200	84.2	0.160	0.281	5.14	0.41								
1300	85.0	0.162	0.281	5.20									
1400	84.7	0.164	0.277	5.28									
1500	85.1		0.276	5.39									
1600	85.1		0.273										
1700	84.5		0.268										
1800	84.3		0.265										
1900	84.9		0.264										

[a] disk ϕ 150 mm and ≠45 mm, upset forged with 71% hot-work, heat treated for 6 h at 1000°C, typical values.

rhenium. Only recently mockups for plasma facing components in Tokamaks using bulk W–5Re were subjected to neutron irradiation [34,55].

W–5Re is mainly used in thermocouples due to its chemical stability, and high-*Z* coatings (preferably made of W–10Re) for extreme thermal shock loading, such as the top layer in X-ray targets.

5.3. Cast tungsten

The maximum allowable oxygen content in arc-cast tungsten alloys with 30 ppm is ~10 times lower than in the comparable powder-metallurgical alloys [1], attributable to the tendency of reactive metals in the PM product to form oxides during sintering. Because of the larger grain size, are-cast alloys are difficult to process into sheets or wires.

However, recently a weakly alloyed tungsten (W–Mo–Y–Ti) has been developed [16]. This material is produced by vacuum melting and then cold deforming. The addition of the reactive elements Y and Ti reduces the amount of free oxygen and carbon, resulting in improved mechanical properties. Prior to armoring wider areas in a fusion machine, the database for that material has to be established.

5.4. W–Cu pseudo-alloys

W–Cu is a composite material produced by infiltration of pre-sintered porous tungsten by liquid copper. Due to the coherent copper a high overall thermal conductivity is achieved. Such materials are widely used for spark erosion electrodes, and for contacts in high voltage switches because of the low erosion [3]. By changing the W:Cu ratio, the thermal expansion can be adjusted to values between 6×10^{-6} and 12×10^{-6}/K [3,62]. There is a good wettability of solid tungsten by liquid copper, but there is (almost) no mutual solid solubility. Therefore W–Cu is not an alloy: it is a composite material consisting of two components. This could have a (negative) impact on the corrosion as well as neutron irradiation resistance.

Although attractive for its very good thermal conductivity (~300 W/mK at RT), the low melting point of copper (~1083°C) limits the application to temperatures below 1000°C. However, compared to copper base alloys such as CuCrZr, the thermochemical properties of W–Cu are not impaired due to treatment or longer application up to 1000°C. The machinability at RT is excellent, the price for the raw material as low as for technical tungsten. Such W–Cu is an attractive candidate material for the heat-sink as well as armor, either when coated with pure W, or uncoated to take advantage of the evaporation cooling effect, as proposed recently [12].

6. Copper alloys for the heat-sink

The high thermal conductivity of copper and its alloys is the primary reason for use as heat-sink in high heat flux components. Therefore water cooled heat-sinks of any component receiving substantial power densities are preferably made of copper(alloys). The other material properties of interest besides thermal conductivity are strength, fracture toughness, ductility, thermal stress factor, thermal fatigue and resistance to neutron damage. As a consequence of the high quantity of copper to be used in high heat flux components of future fusion machines, and also being already widely used in present plasma experiments, there is a recognizable commercial interest, and a well-established industrial experience base for fusion application. An impressive number of reports describing the R&D of copper alloys for fusion has been published in the past – in particular since chosen as reference for the heat-sink of ITER [30,63–70], to mention only some recent review papers.

For a reliable and durable bonding of tungsten armor to copper above all the big mismatch in thermal expansion (see Table 1) has to be overcome. Due to the good wettability of tungsten by liquid copper in general no special surface pre-treatment is needed prior to joining. Good brazability and/or weldability, high plasticity, no temperature limit in the fabrication process, and above all a close match in thermal expansion are the desired properties for “convenient” bonding to tungsten. Obviously, there is no copper-base alloy that would meet all these requirements. Instead, a well-balanced set of material properties and manufacturing parameters has to be found here.

Of all the copper alloys being discussed for application in ITER, only the precipitation hardened CuCrZr and dispersion-strengthened DS-Cu are included for comparison in Table 1. Both alloys exhibit similar values for the listed properties. The main differences between these two are the maximum allowable temperature of application (lower for CuCrZr – limiting the range of coolant temperature), and weldability (poor, if any for DS-Cu – not permitting all routes of component fabrication), see e.g. [71–73].

A reinforcement of copper with carbon fibers leads to a remarkable improvement in strength in the direction of reinforcement. In addition, in fiber direction the thermal expansion of such CFR-Cu materials can rather easily be adjusted to the value of e.g. tungsten. Interface stresses in W/CFR-Cu duplex structures are minimized for any temperature/swing. Same as for W–30Cu, the expected temperature limit for application is the melting of copper – see Table 1. So far flat and tubular geometries were realized, where the desired thermal expansion is adjusted along a flat (bonding) interface, or at the outer tube circumference [74–76]. First VPS-W coatings on flat CFR-Cu substrates appear to be of good quality, thermal shock tests and n-irradiation are planned.

It is to be noted here that a low-expansion/high-melting/high-Z heat-sink for tungsten armor would give a wider margin in passive safety, eliminate problems associated with the big mismatch in thermal expansion between armor and heat-sink, and allow application at higher temperatures. For carbon armor, this was successfully demonstrated already before ITER (e.g. with a flat [77], or tubular [78] Mo–Re heat-sink), and is presently under development for the next-generation stellarator divertor [79].

7. Bonding of tungsten to a copper heat-sink

For the high melting temperature, plasma facing components armored with tungsten have a wider margin in passive safety when off-normal plasma operation leads to local overheating. Although desirable for an easier replacement and repair, a mechanical attachment of divertor or limiter armor tiles to the heat-sink is not considered for present or next generation fusion machines. From today's point of view, for a flat interface a two-step approach is most promising: first coating the bottom of the tungsten armor with a continuous copper layer, and in a second step joining the flat surface of that copper layer to a copper heat-sink via e-beam welding or diffusion bonding. The tungsten armor can already be pre-castellated to smaller sub-units, or even be composed of rods/fibers like a brush, which have to be dipped into liquid copper to produce the continuous weldable layer. Such a way of bonding, involving active metal casting of copper to the armor tiles followed by lateral e-beam welding, was already successfully applied to combine tungsten and carbon armor on one single coolant tube [71–73], see Fig. 1. In any case the direction of best thermal conductivity of sacrificial tungsten armor should be oriented along the shortest path from the plasma facing surface to the heat-sink.

Even after failure and loss of thermal contact in the armor/heat-sink interface, in a tube-in-tile arrangement (''monoblock''), the armor tiles stay in place, preventing immediate propagation of armor detachment. Because of this advantage in passive safety, in the EU a tungsten armored monoblock with a copper coolant tube is being developed as reference design; first mock-ups should be available for the next n-irradiation campaign.

When pulsed plasma power densities up to 20 MW/m^2 have to be removed, possible measures to overcome early component failure due to the big mismatch in thermal expansion, and due to difficulties associated with a high elastic modulus of tungsten, are: reducing the size of tungsten tiles by subdividing down to a

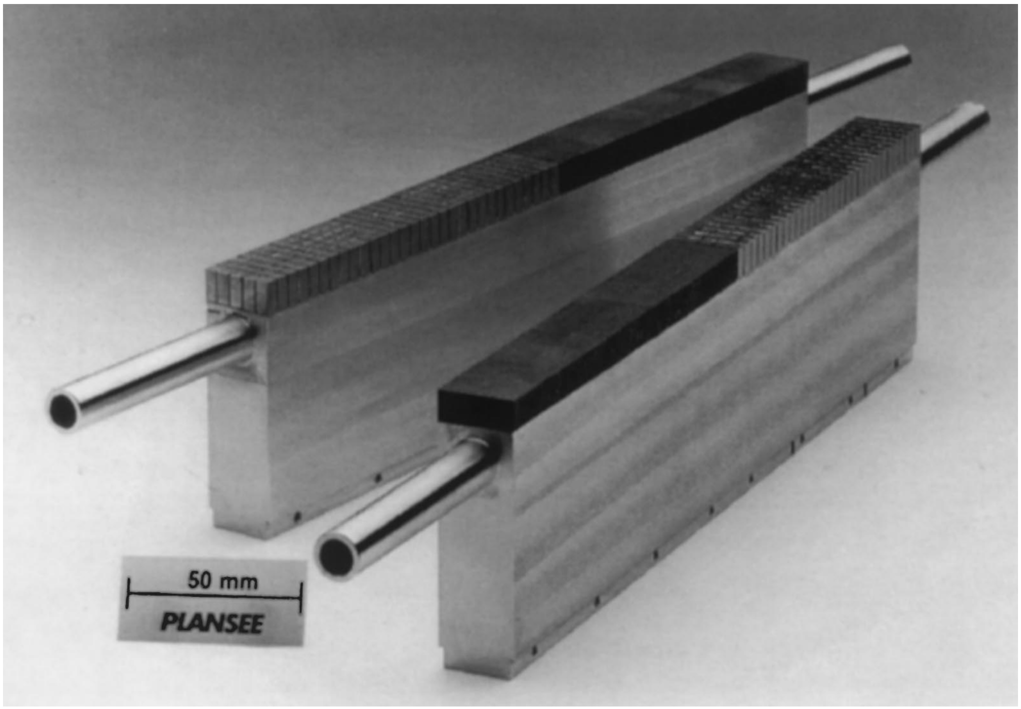

Fig. 1. Mock-ups with tungsten (rods of W–1wt%La_2O_3, 4.5×4.5 mm^2) and CFC armor attached to Cu-alloys via Active Metal Casting and electron beam welding; the tungsten armor survived ~1000 cycles at 16 MW/m^2.

subcritical value (e.g. castellation, brush), introducing interlayers (soft, compliant, or funcionally-graded-materials (FGM)) between armor and heat-sink, or tailoring the thermal expansion of the heat-sink (e.g. CFR-Cu).

For its excellent ductility and compatibility with a whole variety of different materials, silver is a common constituent in many brazes. When Ag is exposed to a fusion neutron spectrum, Cd is the transmutation product fastest formed. Because of the very high vapor pressure of cadmium, 12 (!) Pa at T_{melt} (321°C), silver-free brazes are to be preferred in a vacuum environment when neutrons are present [100]. Newly developed methods for bonding tungsten to copper, where no additional braze filler metal is needed, are to be preferred here [73].

Different methods for bonding tungsten armor to a copper heat-sink were proposed and demonstrated [18,35–37,71–73,80,81]. A comparison of the methods preferred for ITER is found in these proceedings [16].

8. CVD-W and VPS-W coatings

To combine a thin tungsten plasma facing layer with a highly conductive heat-sink, coating of a copper (base) alloy is the first choice. Also, compared to e-beam welding or brazing of bulk armor tiles, coating e.g. via plasma spraying qualifies better for in situ repair.

Although coatings are more appropriate for protective than sacrificial thicknesses, the fusion community succeeded to adapt the chemical-vapor-deposited tungsten (CVD-W) method to produce thicknesses up to 10 mm [82] on W–30Cu substrates. The reason for using these substrates here is that the difference in thermal expansion between W and W–30Cu is a factor of ~2 smaller than between W and Cu-base alloys. CVD-W shows an excellent resistance to thermal fatigue loading up to 20 MW/m^2 [83,84], as well as good thermal shock resistance up to 2 GW/m^2, especially when the W is pre-heated above the DBTT [85,86]. The major concern for thorough use of CVD-W coatings in ITER are the very low deposition rate, and high costs of fabrication [34]. In Fig. 2 the typical process parameters for CVD-W, and one manufactured mockup for high heat flux testing is presented.

For heat-flux regions to receive 5 MW/m^2 or less, plasma spraying could be an economical alternative, with high deposition rates, and a better chance of in situ repair after melting or damaging off-normal plasma events. Plasma-sprayed tungsten (PS-W) has a distinct pancake grain structure, the flat grain oriented parallel to the substrate surface. Possible substrate materials for PS-W are W–30Cu, DS-Cu or CuCrZr (see Table 1). To accommodate the mismatch in thermal expansion, in any case a graded interlayer of sprayed W–Cu can be applied. Especially when coating CuCrZr, the substrate temperature during deposition should be kept well below 400°C in order to avoid over-aging. For tungsten protective and sacrificial coatings, CFR-Cu could serve as low-expansion substrates with high strength and high thermal conductivity, see Table 1.

The thermophysical properties of CVD-W are typically (at least) as good as of pure W, whereas due to the texture and residual porosity in PS-W only ~20% of that thermal conductivity are reported [87]. When the coating is performed in a low-pressure inert argon atmosphere (VPS, "vacuum"-plasma-spraying), VPS-W coatings with ~60% of the thermal conductivity measured for pure tungsten are achieved [88].

Compared to VPS-W, physical-vapor-deposition of tungsten (PVD-W) coatings are of superior density and

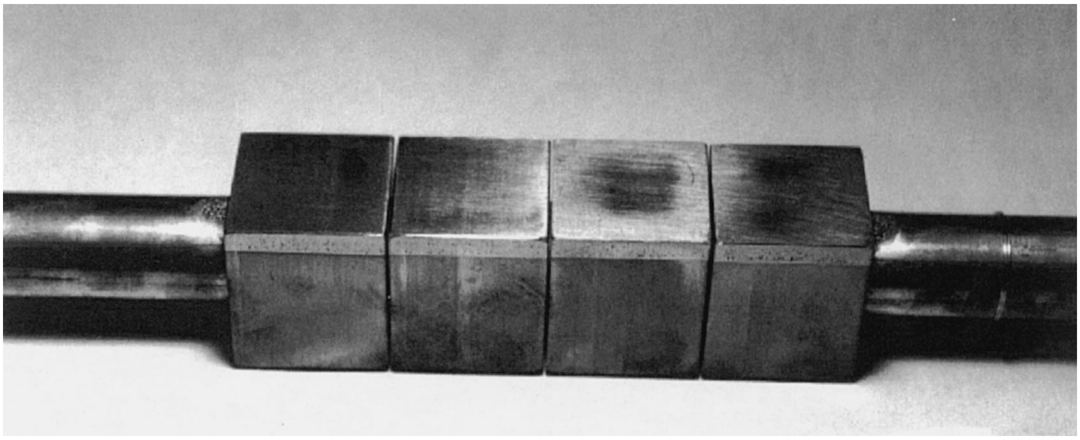

Fig. 2. Five mm chemical-vapor-deposited tungsten (CVD-W) on a water-cooled W-30wt% Cu heat sink; parameters of the CVD process: working gas WF6, T_{env} 700–750°C, coating rate 0.2 mm/h.

thermal conductivity; dense layers of W on a W–Cu substrate – applying a graded intermediate layer – were reported recently [89]. However, this not necessarily translates to a better thermal shock resistance [10]. Also, similar as for CVD, deposition rates for PVD are low, and costs are rather high.

For present-day fusion experiments, W coatings on substrates other than copper (e.g. graphite, CFC) are being developed [5,10,12,15,19,20,90–95]. Such coatings are interesting for short pulsed medium-high heat fluxes, where no active water cooling is needed.

9. Thermal loading and non-destructive inspection of tungsten high heat flux armor

To simulate reactor relevant loading conditions, in the fusion community preferably electron beam testing devices are used [71–73,80,81]. When larger components and larger areas are to be loaded, ion beam facilities, as typically developed for neutron beam injectors, can be applied. The maximum allowable heat flux and number of cycles before damage is of interest for general design considerations and lifetime estimates, whereas loading above the performance limit allows to predict the response under off-normal operation and to study typical failure mechanisms.

Because in tungsten alloys there is a lack of ductility at low temperatures, and there is a big mismatch in the thermal expansion in combination with a copper heat-sink, more than just one extreme loading pattern has to be applied: loading with ultra-short intense thermal pulses to evaluate the thermal shock resistance, and fatigue as well as loading with longer pulses and heating larger areas to evaluate the performance limit of the bonding interface.

The best performance achieved for macro-brushed armor made of W–1%La_2O_3 (consisting of 4.5×4.5 mm^2 rods, embedded in Cu, and e-beam welded to a CuCrZr heat-sink [73], see Fig. 1) was ~1000 cycles at 16 MW/m^2 prior to first failure. PS-W (5 mm of PS-W on CuCrZr) survived 1200 cycles at 2–4 MW/m^2 without failure [87], whereas chemical-vapor-deposited tungsten (2 mm of CVD-W on OF-Cu or W-30Cu) survived 1000 cycles at 5 MW/m^2. The latter also endures heat fluxes up to 22 MW/m^2 for 10 s without failure [83,84].

When exposed to thermal shock loading at heat fluxes of 2 GW/m^2 and higher, the measured weight loss due to erosion is smallest for CVD-W, followed by sintered W, and highest for micro-brushed tungsten [85,86]. Crack initiation and propagation is considerably reduced when the loaded material is pre-heated above the DBTT, even when surface melting occurs [19,20,28,29,96,97]. Also, the erosion resistance in W–Re alloys drops as the Re-content is increased [11].

As a consequence of recent improvements in ultrasonic detectors and data acquisition/processing, the resolution of defects (down to sizes of ~0.1 mm) in bonding interfaces, and short scanning times became acceptable for routine non-destructive inspection of full-size components [98,99]. This is expected to have a crucial impact on the inspection of hybrid in-vessel components during fabrication, before assembly and in-service, as well as on the interpretation of failure mechanisms.

10. Summary

The actual and intended use of W as plasma facing armor so far was based on the experience and materials database from existing commercial application, rather than to stimulate the development of new alloys.

Besides fabrication, the raw materials, the alloying elements and dopants/impurities, pre- and post-treatment, and the final shape/geometry have a strong impact on the achieved properties of tungsten. Future materials R&D should address these issues in more detail. Alternative alloys for the heat-sink with a thermal expansion closer to tungsten were highly attractive.

The commercially available tungsten alloy W–1%La_2O_3 was selected as reference high-Z armor for the divertor and baffle of ITER because of the well balanced material properties, experience in other areas of application, lower costs for the raw materials and machining, as well as absence of high neutron fluence in the basic performance phase. W–5Re is attractive for the better ductility at low temperatures, and besides reduced swelling is expected to suffer less overall radiation damage. CVD-W coatings on W–30Cu show very good performance under high heat fluxes and thermal shocks, VPS-W could be an acceptable low-cost alternative.

Active metac casting, with lateral e-beam welding has proven to be a robust method for joining tungsten (and CFC) armor tiles to a copper heat-sink; also, presently a tungsten monoblock geometry is being developed for higher passive safety.

If exposed to thermal shock loading, CVD-W and also pure sintered W show a better erosion resistance than micro-brushed tungsten; the erosion resistance in W–Re alloys drops as the Re-content is increased. Crack initiation and propagation is considerably reduced when the loaded material is preheated above the DBTT.

If the fusion community continues to consider a wider use of tungsten armor in future fusion reactors, neutron irradiation of all high-Z candidate materials – preferably already joined to the heat-sink, at all temperatures and fluences of interest becomes indispensable. Also, the presently available materials database does not allow a reliable assessment of all safety issues.

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