



Joining of tungsten with low-activation ferritic–martensitic steel and vanadium alloys for demo reactor

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ABSTRACT

The conceptual designs of the blanket and the helium-cooled divertor of the DEMO reactor require joining of reduced activation steel (for example RUSFER EK-181, EUROFER, etc.) and tungsten. Significant differences in their physical properties can lead to the generation of the stresses during cooling and, as a result, to the failure of the joint. In this paper, diffusion brazing of RUSFER EK-181 steel with tungsten using a V–4Ti–4Cr interlayer was obtained. Rapidly-quenched ribbon brazing alloys based on copper of various compositions were used. Brazing was carried out in vacuum furnaces at temperatures in the range of 800–1000 °C. The structural-phase states of the joints obtained were studied, the microhardness was measured, and thermocycling tests were performed in the interval of 700 to 25 °C. FEM simulation was used to calculate the optimal thickness of the interlayer.

1. Introduction

The DEMO thermonuclear reactor is the next step in the development of a commercial thermonuclear reactor. The concepts of the blanket and the helium-cooled divertor require a connection between the reduced activation steel (RUSFER EK-181, EUROFER, etc.) and tungsten. A direct connection between tungsten and steel is practically impossible due to the significant differences in their physical properties, in particular the coefficient of linear thermal expansion (CTE) – $(10.5–12.3) \times 10^{-6} \text{ K}^{-1}$ for steel and $(4.3–6.0) \times 10^{-6} \text{ K}^{-1}$ for tungsten – which can lead to large residual stresses during cooling, and consequently destruction of the joint.

One of the most widespread technologies for joining materials with disparate CTE values is diffusion bonding [1–4], in which materials with an intermediate CTE value (V, Ta, Cu, etc.), or functionally graded interlayers [5], are used to reduce the stress level. In our opinion, diffusion brazing (also known as transient liquid phase bonding) is more preferable because of its simplicity. The promising nature of this method is described in [6,7]. However, many studies in this field were carried out using brazing alloys that consist of high activation elements [8–11]. There are only a few works where the brazing alloys consist of reduced activation elements [12–14]. Of these, electrochemical deposition of layers is necessary in [12]; in [13] the melting points of the brazing alloys are too high; and in [14], a powder-based brazing alloy is used – powder alloys lead to the formation of a thick seam with a

complex heterogeneous structure, and moreover, it should be taken into account that the use of powders complicates the technological process of creating a connection of complex geometry. From this point of view, ribbon-based brazing alloys obtained by rapid quenching technology are convenient. Therefore, in this paper, rapidly quenched ribbon brazing alloys were used to solve the problem of joining steel with tungsten for DEMO application.

2. Materials and methods

The work comprises experimental results of microstructure observations and thermocycling tests of brazed joints: W/EK-181, W/interlayer/EK-181, EK-181/V–4Ti–4Cr. Modeling was carried out by the finite element method (FEM). The brazing alloys' compositions were chosen with consideration to the requirement of reduced activation, i.e. residual activity of the material a hundred years from the end of operation should be no more than 10^{-2} Sv/h [15]. Cu residual activation is a bit higher than this $-3.39 \times 10^{-2} \text{ Sv/h}$ [16], but has the same power. So Cu was chosen to be the base material as it gives the possibility of making brazing alloys with a low melting point. Moreover, Cu is a prospective element with which high performance copper alloys can be developed for DEMO applications [17]. To reduce the amount of copper used, it was alloyed with low-activation elements, Ge and Ti, which have residual activities of 9.32×10^{-10} and $1.16 \times 10^{-3} \text{ Sv/h}$ respectively [15].

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Section 3.1 presents the results of brazing of the ferritic–martensitic steel RUSFER EK-181 (Fe–12Cr–2W–V–Ta–B, wt.%) [18–20] directly to tungsten 99.96%. The materials were of cylindrical form, with radius $r = 10$ mm and height $h = 10$ mm. The brazing alloy used was Cu–50Ti (wt.%) (STEMET 1203), rapidly quenched into ribbons of $50 \mu\text{m}$ thickness. The microhardness of the brazed joint was measured and thermocycling tests were carried out.

Section 3.2 presents the FEM calculation results of the simulated cooling of the W/interlayer/EK-181 assembly from 1100°C to 25°C for various interlayer thickness. V and Ta were chosen as the interlayer material. Calculations were performed for cylindrical samples of radius $r = 10$ mm, height $h = 10$ mm.

Data on density (ρ), CTE (α), Poisson's ratio (ν), and stress–strain true curves were used in the calculations. For getting stress–strain true curves for vanadium, tantalum, and EK-181 steel the Ramberg–Osgood model [21] was applied. By this model, the stress–strain curves are described by the following:

$$\varepsilon = \frac{\sigma}{E} + K \left(\frac{\sigma}{\sigma_{0.2}} \right)^n \quad (2.1)$$

where ε is true total strain, σ is true stress, E is elastic modulus, K is strength coefficient, $\sigma_{0.2}$ is yield strength, and n is the strain hardening exponent. The properties are taken from [22,23] for EK-181, from [24–26] for vanadium, and from [25–27] for tantalum. The coefficients K and n depend on the elastic modulus (E), yield strength ($\sigma_{0.2}$), true ultimate tensile strength (σ_u), total strain at stress equal the yield strength ($\varepsilon_{0.2}$) and total strain at stress equal the ultimate strength (ε_u) by Eqs. (2.2) and (2.3):

$$K = \varepsilon_{0.2} - \frac{\sigma_{0.2}}{E} \quad (2.2)$$

$$n = \frac{\log \left[\left(\varepsilon_u - \frac{\sigma_u}{E} \right) \right] - \log [K]}{\log \left[\frac{\sigma_u}{\sigma_{0.2}} \right]} \quad (2.3)$$

Values of strains are taken from stress–strain curves. The coefficient K is the difference between the total and elastic strain at a stress equal to the yield strength. Its value is taken for all materials to be the same ($K = 0.002$).

A bilinear model was used to describe the stress–strain curve of tungsten. The bilinear stress–strain curve was calculate from the values of elastic modulus (E), yield strength ($\sigma_{0.2}$), and tangent modulus (τ). Properties of tungsten were taken from [28–30].

All the properties are listed in Table 1. In this table, the values given are of engineering strength and strain; they were converted to true values before use. The influence of creep was not taken into account.

Section 3.3 presents the use of a V–4Ti–4Cr (wt.%) interlayer with a Cu–50Ti (wt.%) brazing alloy. The ferritic–martensitic steel RUSFER EK-181 (Fe–12Cr–2W–V–Ta–B, wt.%) [18–20] and tungsten 99.96% were of cylindrical form, with radius $r = 10$ mm and height $h = 10$ mm. The V–4Ti–4Cr alloy used for the interlayer was also of cylindrical form, with radius $r = 10$ mm and height $h = 1$ mm. The brazing alloy used was Cu–50Ti (wt.%) (STEMET 1203), rapidly quenched into ribbons of $50 \mu\text{m}$ thickness. The microhardness of the brazed joint was measured and thermocycling tests were carried out.

Section 3.4 presents two Cu–Ge brazing alloys, used to join the ferritic–martensitic steel RUSFER EK-181 with the V–4Ti–4Cr (wt.%) alloy. The steel was of cylindrical form, with radius $r = 10$ mm and height $h = 10$ mm; the V–4Ti–4Cr was also of cylindrical form, with radius $r = 10$ mm and height $h = 1$ mm. The brazing alloys used were Cu–12Ge and Cu–25Ge (wt.%), rapidly quenched into ribbons of $50 \mu\text{m}$ thickness. The microhardness of the brazed joints were measured and thermocycling tests were carried out.

Table 2 lists the diffusion brazing modes that were made in Sections 3.1, 3.3, and 3.4. Brazing was carried out in a vacuum furnace ($p < 10^{-5}$ mmHg). The process was carried out in special molybdenum

Table 1
Properties of the materials used in FEM simulation.^a

T, °C	ρ , kg/m ³			E, GPa			$\sigma_{0.2}$, MPa			σ_u , MPa			τ , GPa			ε_u			ν			α , $0 \cdot 10^{-6} \cdot ^\circ\text{C}^{-1}$				
	S	W	V	Ta	S	W	V	Ta	S	V	Ta	S	W	V	Ta	S	W	V	S	W	V	S	W	V	Ta	
22	7770	19,300	6110	16,690	215	398	125	185	700	1360	230	296	363	1.3	0.16	0.18	0.25	0.28	10.4	4.4	4.4	10.4	4.4	4.4	8.4	6.3
200	7720	19,250			190	397	123	175	660	1154	170	200	336	1.2	0.15	0.10	0.13		11.2	4.5	9.8	11.2	4.5	9.8	6.6	6.6
400	7665	19,200			185	394	121	166	600	947	166	180	349	1.1	0.13	0.16	0.24		11.9	4.6	11.1	11.9	4.6	11.1	6.8	6.8
600	7600	19,150			172	389	119	160	400	764	120	150	328	1.0	0.23	0.35	0.17		12.5	4.7	11.6	12.5	4.7	11.6	6.9	6.9
800	7540	19,100			165	379	117	155	190	604	86	100	220	0.9	0.30	0.22	0.27		12.7	4.8	12.3	12.7	4.8	12.3	7.0	7.0
1000	7470	19,050			158	373	115	152	100	464	43	75	144	0.8	0.40	0.30	0.33		12.8	4.8	12.7	12.8	4.8	12.7	7.1	7.1
1100	7450	19,000			130	350	114	150	70	345	30	56	116	0.7	0.46	0.40	0.40		12.9	4.9	13.2	12.9	4.9	13.2	7.2	7.2

^a S –EK-181 steel.

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