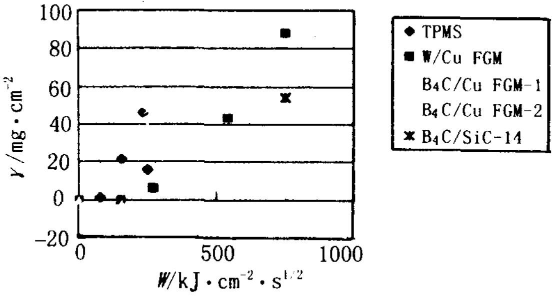

Fig. 1 wight loss rate vs parameter *W* for high purity graphite and functionally graded materials

or SiC were evaporated and exfoliated in the dot. Therefore, we can measure the weight loss of samples. As comparing, the weight loss rate of high purity graphite TPMS is also listed in Fig. 1. It is obvious that the weight loss rate of W-Cu FGM is lower than that of graphite.

From Table 1, it can be seen that the main damage mechanisms of W-Cu FGM is oxidation layers exfoliation, re-crystallization, grain boundary thermal stress fracturing, evaporation and cracks, chemical decomposition (redeposition) with the increasing of power density. As for B_4C-Cu FGMs, cross section SEM photograph showed cracks and fracturing occureed on the interfaces of the sample with Ni as medium layer under 300 times laser shots with power density 398 MW · m^{-2} and so not for the sample with Cu as medium layer. For SiC samples, SiC and SiC/C with out functional medium show very poor properties, all three samples were broken into several pieces during 20 ~ 100 times laser pulse shots with power density 398 MW · m^{-2}. As a word, FGMS show better capability to withstand high heat loads and integrity under thermal cycling, material synthesis with functional medium layer is a promising method to design and manufacture PFCs and divertor components.

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2.7 The Development of V-based Alloys

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Key words Vanadium alloy Development

Vanadium alloy has the potential advantages over other structural materials for fusion application. It is not only good in high temperature property, high resistance to neutron irradiation and feasibility of fabrication, but also a typically low activation material. However, the alloy is easily contaminative in the process of fabrication at elevated temperature such as hot rolling, causing the loss in ductility and toughness. In this paper, a process was introduced to prepare several kinds of vanadium alloys.

Pure vanadium, titanium metal and chromium were used to prepare the alloy. Alloys were ac-melted in a magnetic floating furnace. All ingots were then forged, hot-rolled and cold rolled in air to 0.5 ~ 1 mm thick plate. Finally, the plates were annealed at 1 020 ℃ for 1 hour with a vacuum of 1×10^{-3} Pa. Temperature for forging and hot rolling was between 400 and 850 ℃. An acid solution (HNO_3 + 5% HF) was used to remove the surface oxidized layer. Fig. 1 shows the microstructure of the alloys. The grain is fine with an average size of 20 ~ 40 μm. Table 1 listed the chemical composition, mechanical strength, elongation and the temperature of hot work of the alloys developed.

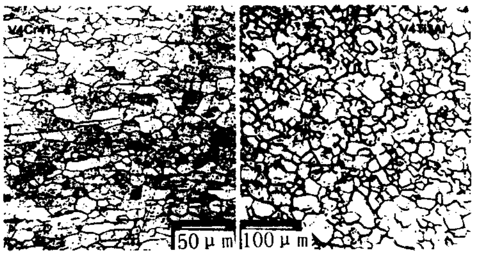

Fig. 1 The microstructure of the vanadium alloys of V4Cr4Ti and V4Ti3Al

The following results could be obtained from the Table 1:

(1) Most of the alloys had very low nitrogen content.

(2) Hot-work temperature had large influence on the oxygen content of the alloys because the alloys were forged and hot-rolled in air. The temperature should not exceed 500 ℃ for the purpose to control the total content of C, N and O being lower than 1×10^{-11}.

(3) The alloy elements Cr, Al, Si and the impurity elements O could strengthen the alloy. Especially Al, it largely increases the strength of the alloy.

(4) The Vanadium alloys with aluminum had relatively lower oxygen content in comparison with the alloys without aluminum element at the same hot work conditions.

Impurities in the alloys may came from the raw materials and from the atmosphere in the process of melting, forging and hot rolling. The raw materials used for the alloy development had high purity. Table 2 listed the impurities in the metal vanadium and titanium. The oxygen content in the V-2 type vanadium was 3.30×10^{-8}, while that in the V4Ti3Al was only 3.90×10^{-8}, if hot work temperature was 400 ~ 500 ℃ (see Table 1). The difference was small, which showed that

Table 1 Chemical composition, mechanical strength, elongation and the temperature of hot work of the alloys developed

alloys	chemical composition weight percent/%							σ_y /MPa	σ_u /MPa	δ /%	T_{hw} /℃
	C	Si	Cr	Ti	Al	N	O				
V4Cr4Ti	0.024	0.023	3.61	4.11	0.21	0.046	0.09	326.3	402.7	19.0	850
V3TiAlSi	0.012	0.95	0.02	3.20	1.07	0.006	0.08	438.5	501.9	19.5	850
V4Ti-1	0.02	0.005	—	1.32	0.19	0.002	0.046	237.8	338.5	26.9	400 ~ 500
V4Ti-2	0.014	0.012	0.22	4.23	0.23	0.002	0.085	262.0	341.5	19.0	850
V4Ti3Al-1	0.019	0.016	—	4.24	2.82	0.001	0.039	404.5	461.6	20.3	400 ~ 500
V4Ti3Al-2	0.019	0.008	0.02	4.23	2.89	0.005	0.07	382.5	425.4	23.0	850
V4TiSi	0.016	0.24	0.02	3.96	0.26	0.052	0.11	256.3	335.7	21.8	850

σ_y: yield strength, σ_u: ultimate strength, δ: total elongation, T_{hw}: hot-work temperature.

Table 2 The impurities in the raw material of vanadium and titanium (in weight percent)

Metal	Type	C	Si	Cr	Al	Fe	N	O
Vanadium	V-2	0.006	0.004	≤0.02	≤0.01	≤0.02	0.006	0.033
Titanium	TAD	≤0.03	≤0.03	—	—	≤0.03	≤0.01	≤0.05

the alloy absorbed small amount of oxygen from the atmosphere during the process of alloy preparation.

Vanadium, titanium and aluminum will be oxidized in the alloy preparation process. Vanadium will take severely oxidization if the temperature exceed 475 ℃. This is the reason that the vanadium alloys had higher oxygen content for the case that the hot work temperature was 850 ℃. However, the vanadium alloy with aluminum had relatively lower oxygen content since the alloy element aluminum played a role to reduce the vanadium oxidizing rate.

2.8 Thermal Shock Test of Graphite by Laser Beam

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Key words Thermal shock Graphite

Graphites are considered as one of the candidate for plasma facing materials (PFM) based on its low atomic number and good thermal shock resistance. The heat load on PFM may be high up to 100 MJ · m^{-2} in several mini-seconds on plasma disruption, which can' t be avoided for the recent tokamak machine. PFM may suffer severe damage such as thermal stress cracking, vaporization and surface erosion by the high heat load and ion irradiation.

Pure graphite has been used as limiter or armor tile in the recent large tokamaks. It has been found to have high chemical sputtering and thermal erosion rate. Recent years, some B, Ti, Si-doped graphites were developed in China. They showed higher resistance to chemical sputtering and thermal erosion than pure graphite[1,2]. It is useful for the material development to establish the relations between the composition, microstructure and the thermal shock behavior. Several graphites with different B, Ti, Si content were shocked by a pulse ND: YAG laser beam. The wavelength is 1.06 μm and the power is 200 W on average. The pulse length of the laser beam was 4 ms with an interval of 96 ms. The power density on the specimen surface reached to 122.9 MW · m^{-2} and 398.1 MW · m^{-2}. Table 1 showed the physical properties of the graphites.

Fig. 1 shows the dependence of the weight loss on the accumulated laser power intensity. Here Φ is the power density, t is