Fabrication and dynamics of two layers vanadium carbide reinforced iron matrix surface composite

Fan Bai¹, Li-sheng Zhong^{a,1}, Xin Wang¹, Yun-hua Xu¹, Zi-yuan Zhao¹

¹*School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China*

Abstract. Vanadium carbide particulates-reinforced iron matrix composites were prepared by in situ solid-phase diffusion method with different heat treatment times (30, 60, 120 and 240 min) at 1223 K, 1273 K and 1323 K after high temperature treatment at 1373 K for 5 min. The surface vanadium carbide layers (V_2C layer and V_8C_7 layer) were characterized by means of scanning electron microscopy and X-ray diffraction. The kinetics of vanadium carbide layers showed that a parabolic relationship between carbide layer thickness and treatment time, which indicating that the composite layer's growth is controlled by diffusion. The apparent activation energy of V_2C layer and V_8C_7 layer were 47.27 kJ/mol and 32.26 kJ/mol, respectively.

1 Introduction

It is well known that vanadium carbide is one of the most appropriate reinforcement for iron matrix surface composite, which due to its high hardness, good thermal stability, and well wettability with iron matrix [1]. Vanadium carbide reinforced iron matrix surface composite shows excellent wear resistance and high temperature properties, which can be widely used in metallurgy, mining, power, machinery, and water conservancy [2]. The diffusion dynamics based on the Arrhenius equation of carbide coating [3], boride coating [4], and nitrogen coating [5] on the surface of steel or iron matrix have been reported elsewhere. S. Barzilai and N. Frage [3] have developed an effective method, which thin films of niobium ($\sim 8 \mu\text{m}$) were deposited on an ATJ graphite substrate by radio-frequency magnetron sputtering at low temperatures ($420 \pm 50 \text{ K}$) under argon pressure of 0.67 Pa. It was found that the activation energies are 190 kJ/mol for Nb_2C , 164 kJ/mol for NbC , and 169.4 kJ/mol for the combined carbide layers, respectively.

The main goal of this study is to study the kinetics of two layers vanadium carbide (V_2C and V_8C_7) reinforced iron matrix surface composite, which were prepared by solid phase diffusion reaction.

2 Experimental procedures

The main raw materials for preparing two layers vanadium carbide are vanadium plate (wt.%, 99.97 V) and gray cast iron (wt.%, 2.57C–1.04Mn–1.03Si–0.046P–0.018S). The two layers vanadium carbide reinforced iron matrix surface composite were prepared by solid-phase diffusion reaction process. The details of

the process are presented in the author's prior work [6]. Each specimen was heated to 1373 K and maintained for 5 min, followed by incubation at 1223, 1273, and 1323 K for 30–240 min in a horizontal tube furnace with a modest flow of argon (5 mL/min).

After being polished with diamond paste and etched with a 4% Nital solution, the microstructures of specimens were examined using a JSM-5800 scanning electron microscope (JEOL, Japan) equipped with an energy dispersive X-ray spectroscopy (EDS). The X-ray diffraction (XRD) data were recorded on a PW 1730 X-ray diffractometer (Philips, The Netherlands) with monochromated $Cu K\alpha$ radiation at 40 kV and 40 mA in the 2θ range of 20° – 90° .

3 Results and discussion

3.1 Microstructure of the vanadium carbide reinforced iron matrix surface composite.

Fig.1 is the microstructure of the vanadium carbide reinforced iron matrix surface composites by incubation at 1223 K for 30 min, 60 min, 120 min, and 240 min after high temperature treatment at 1373 K for 5 min, respectively. It is clear that, there are two dense and compact layers between vanadium plate and the matrix, which have good bonding to the gray cast iron. In detail, the longitudinal cross-section microstructure of the composite can be divided into two layers: light gray layer (I) and dark gray layer (II). The location of layer I is close to the vanadium plate, and its thickness are only 6–15 μm with dense carbide. Layer II shows less density and carbide distribution with 21–61 μm in thickness. Besides, the thicknesses of the layers gradually increase

^a Corresponding author: zhonglisheng@xaut.edu.cn

with the heat treatment times increased from 30 min to 240 min.

Fig.2 is the XRD results of the vanadium carbide reinforced iron matrix surface composites by incubation at 1223 K for 30 min, 60 min, 120 min, and 240 min after high temperature treatment at 1373 K for 5 min, respectively. The XRD results showed that V, V₈C₇, and V₂C are the main phases of the composites. By prolonging heat treatment time from 30 min to 240 min, the intensities of the diffraction peaks corresponding to metallic vanadium decrease along with increasing the intensities of the diffraction peaks of V₈C₇ and V₂C. The author's previous work [7] shows that layer I and layer II are V₂C layer and V₈C₇ dense layer, respectively.

Figure.1. Microstructure of the vanadium carbide reinforced iron matrix composite by incubation at 1223 K for 30 min (a), 60 min (b), 120 min (c), and 240 min (d), after high temperature treatment at 1373 K for 5 min, respectively.

Figure.2. XRD results of the vanadium carbide reinforced iron based surface composites by incubation at 1223 K for 30 (a), 60 (b), 120 (c), and 240 min (d) after high temperature treatment at 1373 K for 5 min.

To obtain more information on the layer I and layer II in the composite, the specimen by incubation at 1223 K for 240 min were examined. According to the EDS

results obtained from the crystalline particles present in each layer, the ratio of vanadium to carbon is 1:0.55 and 1:0.93 for the layers of I and II, respectively, in the specimen heat treated at 1223 K for 240 min. Based on the XRD results, these values are considered to be close to the atomic ratio of V₂C and V₈C₇, respectively.

Figure.3. Two layers thickness increases with treatment time for each process temperature for V₂C layer (a) and V₈C₇ layer (b).

3.2 Kinetics of two layers vanadium carbide reinforced iron matrix surface composites.

The experiments can measure the V₂C and V₈C₇ layers thickness. These measured values can be used to calculate the kinetics parameters of the vanadium carbide reinforced layer. The graphical representation in Fig.3 shows that two layers thickness increases with treatment time for each process temperature. It was observed that the longer the treatment time and the higher the process temperature, the thicker carbide layer became. On the basis of the classical kinetic theory.

Fig.4 shows the square of the layer thickness versus treating time at different temperatures. It is clear that the square of the layer thickness changes linearly with the treating time. The fitted six straight lines in Fig.4 correlation coefficients R² are higher than 0.98, indicating that it is credible that the growth rate constant K at the same temperature conditions is a constant.

In addition, the relationships between the growth rate constant K, activation energy Q, and the process temperature in Kelvin T, can be expressed as an Arrhenius equation [8]:

$$\ln K = \ln(K_0) - \frac{Q}{RT} \quad (1)$$

where K_0 is the pre-exponential constant and R is the gas constant (8.314 J/mol K). Q and K_0 can be calculated from a plot of $\ln K$ versus $1/T$. The activation energy, Q is the slope of line in Fig.5. It can be seen the value of Q for V_2C layer and V_8C_7 layer are 47.27 kJ/mol and 32.26 kJ/mol, and the value of K_0 for V_2C layer and V_8C_7 layer are $7.26 \times 10^{-3} \text{ cm}^2/\text{s}$ and $6.31 \times 10^{-3} \text{ cm}^2/\text{s}$, respectively.

Figure.4. The square of the layer thickness versus treating time at different temperatures for V_2C layer (a) and V_8C_7 layer (b).

Figure.5. A plot of $\ln K$ versus $1/T$ for V_2C layer (a) and V_8C_7 layer (b).

Inserting the values of Q and K_0 in Eq. (1), Eq. (2) are obtained by inserting the calculated value of Q and K_0 . For V_2C layer and V_8C_7 layer, the K are,

$$K = 7.26 \times 10^{-3} \exp\left(-\frac{3930.52}{T}\right) \quad (2)$$

$$K = 6.31 \times 10^{-3} \exp\left(-\frac{3880.03}{T}\right) \quad (3)$$

Then, the relationship among V_2C layer or V_8C_7 layer thickness, treating time and temperature can be obtained.

Conclusions

The kinetics of composite layer showed that a parabolic relationship between carbide layer thickness and treatment time, which indicating that the composite layer growth kinetics is controlled by diffusion. The relationship between growth rate constant and reaction temperature meet the classical Arrhenius Equation. The apparent activation energy of V_2C layer and V_8C_7 layer were 47.27 kJ/mol and 32.26 kJ/mol, respectively.

Acknowledgements

The project was supported by the Shaanxi Natural Science Basic Research Project (2016JQ5044) and the Scientific Research Plan Projects of Shaanxi Education Department (16JK1561).

References

1. X.J. Di, M. Li, Z.W. Yang. Mater.Des. 96 (2016)
2. Y.P. Ji, S.J. Wu, L.J. Xu. Wear. 295, 31 (2012)
3. S. Barzilai, N. Frage, A. Raveh. Surf. Coat. Technol. 200 (2006)
4. V. Ataibis, S. Taktak. Surf. Coat. Technol. 279 (2015)
5. H. Liu, J.C. Li, Y.T. Chai. Surf. Coat. Technol. 302 (2016)
6. S.Z. Fan, L.S. Zhong, Y.H. Xu, Y.H. Fu, L.L. Wang. Adv. Eng. Mater. 17, 11 (2015)
7. F.X. Ye, M. Hojamberdiev, Y.H. Xu. Appl. Surf. Sci. 280, 8 (2013)
8. M. Aghaie-Khafri, F. Fazlalipour, J. Phys. Chem. Solids. 69, 10(2008)EPL, 84 (2008)