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EXAMINATION OF CARBON DIFFUSION IN TANTALUM CLAD STEEL COMPOSITE①

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ABSTRACT The Ta_2C layer formed in the bonding interface of a tantalum clad steel composite with an intermediate layer of pure iron at 1 053 K for different times was examined metallographically and analyzed using the electron microprobe technique. The mechanism of Ta_2C phase diffusion layer formation was discussed using Fick's law assuming that stationary diffusion of carbon was established in tantalum/steel diffusion couples.

Key words Ta_2C-phase carbon activity stationary diffusion

1 INTRODUCTION

The tantalum clad steel composite is a clad steel plate, of which the base metal is steel with 0.20% carbon and the cladding metal is tantalum with excellent corrosion resistance and heat resistance, and is utilized in many engineering fields, such as in boilers for corrosive media, reactors. For producing tantalum clad steel composite, in general there are an explosion bonding process in which materials are bonded by powder explosion at room temperature[1] and a hot rolling process in which a slab assembly is heated and hot-rolled. The explosion bonding process is excellent in bonding, but the cost is high, and is restricted by producible sizes. The hot rolling process is more popular for the production of stainless steel clad plates and applicable to mass-production, however, it is not suitable for production of tantalum clad steel plate. Usually, the carbon is transferred to the tantalum and the tantalum is characterized by Ta_2C layer on parts to be cladded during hot rolling.

The present authors[1] examined the Ta_2C phase formation and the diffusion path in the tantalum-steel explosion weld interface. The Ta_2C layer between tantalum and steel generally has a negative influence on its performance. For producing the tantalum clad steel plate via hot rolling, one way to decrease carbon diffusion is to introduce an intermediate metal layer. In the present work, an intermediate layer of pure iron was introduced by hot rolling, the purpose of the paper is to examine the role of such a layer in the tantalum clad steel composite.

2 EXPERIMENTAL

The specimens were prepared from the tantalum clad steel composite with an intermediate layer of pure iron. The samples were sealed into the quartz capsules under vacuum (10^{-2} Pa) and annealed at 1 053 K for different times in the GK-2B type diffusion furnace. The temperature was controlled with a thyristor regulator and was found to be within ±1 ℃. After the heat treatments, the samples were water quenched by breaking the capsules. The quenched specimens were ground, polished and etched in an aqueous alcohol solution containing 3% nitric acid. All samples were investigated using microscopy (Neophot 21) and electron microprobe analysis (Camebax-Micro and X-650).

3 RESULTS AND DISCUSSION

Fig. 1 shows an optical micrograph of a tan-

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talum clad steel composite. The strongly deformed grains were noticeable within the three layers of the composite, the interface between tantalum and pure iron is characterized by the existence of a reaction layer about 1 μm thick. Longer heat treatments at 1 053 K caused further growth of the reaction layer and the thickness of the reaction layer was increased. Fig. 2 shows a scanning electron micrograph in the interface of tantalum/ iron, and the distribution of carbon element. A thickening diffusion layer is evident in the interface of tantalum/ iron, its thickness is about 6 μm. The EPMA result shows that a large amount of carbon was distributed within the reaction layer. From quantitative electron microprobe analysis of the reaction layer, the tantalum content ranges from 67.3% to 69.2% (mole fraction), the carbon content ranges from 31.8% to 29.1% (mole fraction) and the solid solubility of iron in the Ta_2C phase ranges from 0 to 0.5% (mole fraction). Consequently, this layer corresponds to the Ta_2C phase. This implies that most of the carbon diffuses into the tantalum from the steel and reacts to form Ta_2C phase, which is consistent with the low solubility of carbon in tantalum.

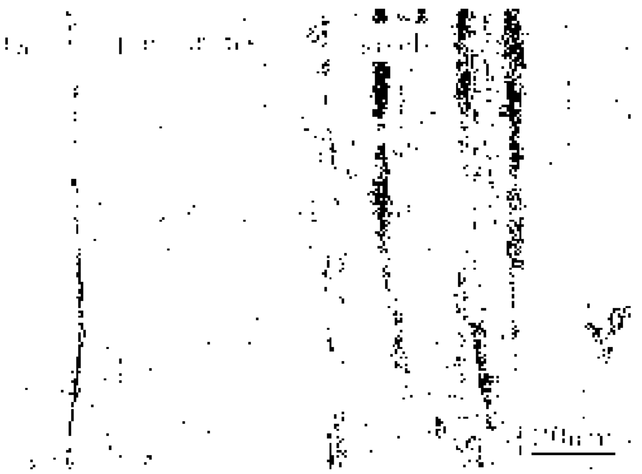

Fig. 1 **Optical micrograph of tantalum clad steel composite with intermediate layer of pure iron after hot-rolling at** 1 053 K

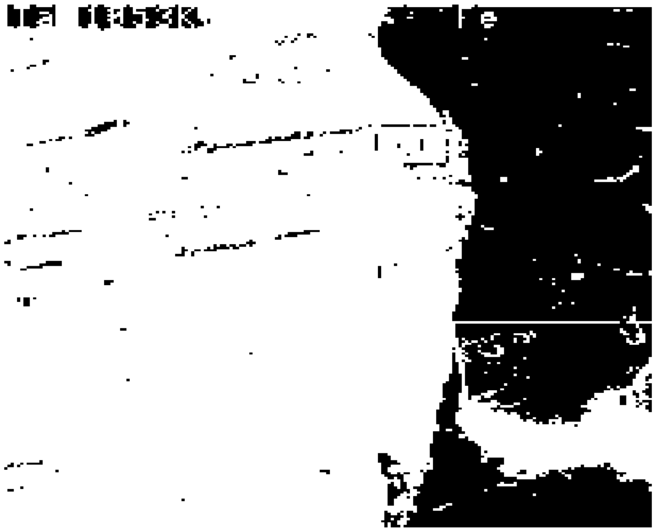

Fig. 2 **Scanning electron micrograph of tantalum-iron bond interface and distribution of carbon element found by EPMA after** 213 h **annealing at** 1 053 K

The intimate connection between ternary phase equilibria of the Fe-Ta-C system and diffusion layer formation was elegantly demonstrated; it was conducted to identify the Ta_2C phase that can be formed at the interface of tantalum/ iron[1]. At 1 053 K the composition of steel is in the two-phase field of α-Fe and γ-Fe. The carbon concentration difference in the γ-Fe phase field results in extensive carbon diffusion and the carbon diffuses from steel with 0.20% carbon to tantalum. The carbon concentration profile in Fig. 2 approximately looks like that in Fig. 3. Fig. 3 shows that the carbon concentration is always much lower in the α-Fe layer than in the γ-Fe and Ta_2C parts. However, as discussed by Ågren[2, 3], the activity of carbon varies contin-

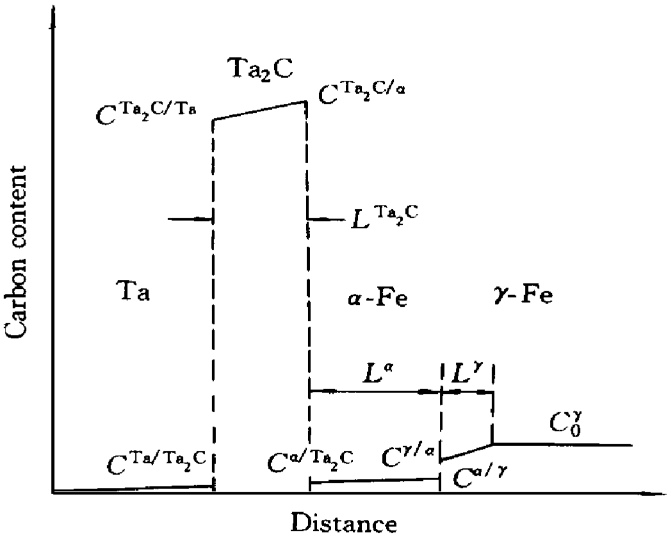

Fig. 3 **Piece-wise linear approximation of carbon concentration profile in Fig.** 2

uously over the joint of the tantalum clad steel composite with an intermediate layer of pure iron. Employing the notation in Fig. 3 yields

$$C^{Ta_2C/\alpha} f^{Ta_2C} = C^{\alpha/Ta_2C} f^{\alpha} \qquad (1)$$

$$C^{\gamma/\alpha} f^{\gamma} = C^{\alpha/\gamma} f^{\alpha} \qquad (2)$$

where f^{Ta_2C}, f^{γ} and f^{α} are respectively the activity coefficients of carbon in different parts of the joint. For times longer than the relaxation time for carbon diffusion in the intermediate layer of pure iron, the change of the carbon content in the pure iron layer can be neglected compared with the change in the Ta_2C and γ-Fe parts and the stationary diffusion of carbon has been established. The outgoing flux of γ-Fe phase must equal the flux through pure iron and the ingoing flux in Ta_2C phase. Employing Fick's law and the notation in Fig. 3 yields

$$D^{Ta_2C}\left[\frac{C^{Ta_2C/\alpha} - C^{Ta_2C/Ta}}{L^{Ta_2C}}\right] = D^{\alpha}\left[\frac{C^{\alpha/\gamma} - C^{\alpha/Ta_2C}}{L^{\alpha}}\right] \qquad (3)$$

$$D^{\gamma}\left[\frac{C_0^{\gamma} - C^{\gamma/\alpha}}{L^{\gamma}}\right] = D^{\alpha}\left[\frac{C^{\alpha/\gamma} - C^{\alpha/Ta_2C}}{L^{\alpha}}\right] \qquad (4)$$

where D^{Ta_2C}, D^{γ} and D^{α} are respectively the diffusivities of carbon in the Ta_2C, γ-Fe and the pure iron layer. The distances L^{Ta_2C} and L^{γ} are approximated with the well-known expressions from random walk theory

$$L^{Ta_2C} = \sqrt{2D^{Ta_2C}t} \qquad (5)$$

$$L^{\gamma} = \sqrt{2D^{\gamma}t} \qquad (6)$$

By combining Eqs. (1) to (6) and solving them for unknown compositions $C^{Ta_2C/\alpha}$, $C^{\gamma/\alpha}$, we obtain

$$C^{Ta_2C/\alpha} = \frac{C^{Ta_2C/Ta} + \sqrt{\dfrac{D^{\gamma}}{D^{Ta_2C}}}\, S^{\gamma}(t)\, C_0^{\gamma}}{1 + \dfrac{f^{Ta_2C}}{f^{\gamma}}\sqrt{\dfrac{D^{\gamma}}{D^{Ta_2C}}}\, S^{\gamma}(t)} \qquad (7)$$

where $S^{\gamma}(t) = \dfrac{1}{\sqrt{\dfrac{D^{\gamma} f^{\alpha}}{D^{\alpha} f^{\gamma}}}\dfrac{L^{\alpha}}{\sqrt{2D^{\alpha}t}} + 1}$

$$C^{\gamma/\alpha} = \frac{C_0^{\gamma} + \sqrt{\dfrac{D^{Ta_2C}}{D^{\gamma}}}\, S^{Ta_2C}(t)\, C^{Ta_2C/Ta}}{1 + \dfrac{f^{\gamma}}{f^{Ta_2C}}\sqrt{\dfrac{D^{Ta_2C}}{D^{\gamma}}}\, S^{Ta_2C}(t)}$$

and $S^{Ta_2C}(t) = \dfrac{1}{\sqrt{\dfrac{D^{Ta_2C}}{D^{\alpha}}\dfrac{f^{\alpha}}{f^{Ta_2C}}}\dfrac{L^{\alpha}}{\sqrt{2D^{\alpha}t}} + 1}$

As mentioned above, the intermediate layer is usually introduced in order to decrease the concentration differences $C^{\gamma/\alpha} - C_0^{\gamma}$, $C^{Ta_2C/\alpha} - C^{Ta_2C/Ta}$ and the amount of carbon diffusion. From Eq. (7) one can deduce that this is achieved by choosing $S^{\gamma}(t)$ and $S^{Ta_2C}(t)$ as small as possible. One should thus choose a material with a large f^{α} and a low D^{α}. However, Eq. (7) also shows that at long diffusion time the intermediate layer becomes gradually less important. It is known that the intermediate layer of pure iron is only slightly different from that of the steel; it is usually not possible to increase f^{α} very much. In order to obtain a strong effect, it is necessary either to use a very thick intermediate layer or to use an intermediate layer of a different metal. As an example, Cu has been reported to have a very low D^{Cu}. It also has a very low solubility of carbon[4, 5] and should thus have a very high f^{Cu}.

For producing the tantalum clad steel composite via hot rolling, a material should be interposed between the tantalum and the steel in order to prevent formation of compounds at the boundary of tantalum and iron. As such intermediate materials, preferable are those metals which make a perfect solid solution with tantalum or iron. Ni, Mo and Nb have been used[6] in foil or have been plated or undertaken with spraying process on a cladding face.

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