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ARTICLE

Precipitation Behavior of Second Phases during Isothermal Oxidation of Hastelloy C-2000 Alloys

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Abstract: The precipitation behavior of the second phase in Hastelloy C-2000 alloy matrix was studied after isothermal oxidation at 800 °C for 100 h in air. Mo-rich phase was precipitated in the alloy matrix after oxidation. According to the determination Mo-rich phase with diamond cubic structure is Mo_3Ni_3C type carbide. Morphology characteristics of Mo-rich phase with both no-continuous and continuous irregular strip are presented along grain boundaries and in matrix, respectively. However, some variation of morphologies will take place at both grains and grain boundaries after deep etching, i.e. a large number of white flocculent structure are distributed along grain boundaries, and the corrosion pits with a diamond structure appear in intragranular. Ni-rich and Cr-rich areas are more easily corroded during deep etching due to a more negative electrode potential in the areas.

Key words: oxidation; Mo-rich phase; Mo_3Ni_3C type carbide; grain boundary; potential

As a new development of Ni-Cr-Mo-based superalloy, C-2000 alloy has been widely used as oil chemical pipelines, coal chemical dust filter, energy and electricity heat exchanger tubes for its excellent corrosion resistance in oxidizing and reducing media. However, superior oxidation resistance is required under the service condition. Therefore, the high temperature oxidation performance of the alloy is an important index for service life [1-7].

The oxidation of an alloy at high temperatures is equivalent to the long-term aging for the alloy, i.e. the precipitation of different phases would take place in the alloy matrix after oxidation. It is well known that various carbides, TCP phases and ordering phases precipitate in both grain boundaries and grains, and their evolution has been extensively reported in the temperature range of 650~900 °C in literatures [8-11]. The influence of the precipitation of second phases on the performance of the alloy is quite obvious. Tawancy et al. [12] reported that the Pt_2Mo superlattice phase in Ni-Cr-Mo alloy could lead to an increase in yield strength of 2~3 fold over the solution strengthened alloy. Casales et al. [13] showed that the corrosion resistance of alloy 600 was associated with semi-continuous to continuous carbides at grain boundaries, with few intergranular carbides. Sahlaoui et al.[14] found that chromium concentration evolution and chromium depleted zones appeared resulting from carbides precipitation during aging of the Ni-Cr-Fe alloys at the carbide-matrix interface and near the grain boundaries intergranular, respectively, so that corrosion resistance properties of alloys were greatly affected. Berthod et al. [15] reported that the dissolution of carbides led to the formation of non-carbides areas in alloy matrix under oxide scales during high temperature oxidation, which would result in both deterioration of mechanical property and decrease of oxidation resistance.

Owing to low carbon contents of C-2000 alloy, which can be seen as a non-carbon alloy, the precipitation behavior of carbides in C-2000 is rarely considered in the service circumstance. Yang et al. [16] studied the oxidation characteristic of Ni-Cr-Mo alloy from 600 °C to 1000 °C by isothermal oxidation, but the precipitation behavior of second phases in matrix during oxidation was not considered by

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authors. However, the precipitation of minute traces of carbides would take place even a low carbon contents during isothermal oxidation temperature of C-2000. As corrosion resistant alloy, the properties of high temperature oxidation of C-2000 are also an important indicator during the service process. It was just to meet the precipitation conditions of second phases in C-2000 alloy during oxidizing atmosphere at 600~800 ^{o}C. Moreover, the precipitation position, the morphology and the distribution of second phases will affect high temperature oxidation properties of alloys once they are precipitated in matrix. Therefore, the significance of the precipitation behavior of second phases in C-2000 will become evident for the application of the alloy. The purpose of this paper is to investigate the precipitation behavior of phase in C-2000 alloy matrix during isothermal oxidation at 800 ^{o}C for 100 h in air.

1 Experiment

The material used in this study was Hastelloy C-2000 alloy supplied by Haynes International Company, whose composition (wt%) is 22.81Cr, 15.55Mo, 1.48Cu, 0.87Fe, 0.24Al, 0.22Mn, 0.08Co, 0.007P, 0.003S, <0.02Si, 0.001C and Bal. Ni. The oxidation tests were carried out at 800 ^{o}C for 100 h in air. After oxidation, oxide scales on surfaces of specimens were completely polished by silicon carbide sandpaper, and then the specimen surfaces were wet-polished up to 2000 grit with a series of SiC sandpapers, and polished successively with 1.0, and 0.5 μm alumina powder suspensions, and then ultrasonicated for 30 min.

The precipitation behavior of second phases in alloy matrix was examined by X-ray diffraction (XRD). Morphologies and chemical compositions of second phases were analyzed by scanning electron microscope (SEM) with energy dispersive X-ray spectrometer (EDS). Transmission electron microscope (TEM) was used to determine structural characteristics of second phases. In addition, samples were etched using HCl and H_2O_2 solution in order to further study morphologies of precipitation phases.

2 Results and Discussion

2.1 SEM-BSE images of alloy matrix after oxidation

The morphologies and the element line scanning of second phases in alloy matrix after oxidation are displayed in Fig.1. Second phases present the no-continuous and continuous irregular strips in grains and grain boundaries, respectively. It is well known that defect density in grain boundaries is higher than that in grains, which results in the formation of continuous gradient in grain boundaries. Meanwhile, dislocations and vacancies are main types of defects in grains, which is consistent with the viewpoint of Zheng et al.[17,18]. Moreover, dark-gray fuzzy spots also emerge in local grains. It is well known that the backscattered electron yield increases with increasing of atomic number. Atomic number fraction of both Ni and Cr elements are less than that of Mo element; therefore, it can be speculated from BSE that both second phases and dark-gray fuzzy spots may be Mo-rich phases and areas of Ni-rich and Cr-rich, respectively. This is consistent with the results of both EDS spectra and the line scanning. Meanwhile, the size of Mo-rich phases was measured by a statistical method, and its size is approximately 4~5 μm (Fig.1b). It can be found from XRD (Fig.2) that the position and the width of diffraction peaks are not dramatically changed compared with the original alloy matrix. Due to volume fractions of phases less than detective range of X-ray, diffraction peaks of Mo-rich phases do not appear, either.

The oxidation of an alloy at high temperatures is equivalent to the long-term aging, namely temperature and time provide thermodynamics and kinetics conditions for the precipitation of second phases. It is well known that grain boundary is fast diffusion paths channels of elements[19]. Mo atoms would quickly migrate from the alloy matrix to grain boundaries with volatilizing Mo oxides; as a result, a concentration gradient of Mo is formed from grains to grain boundaries. This moment, other major alloying elements such as Ni and Cr will also start to diffuse toward the interface between alloy and gas, and Ni and Cr oxide scales with an excellent protection performance are formed on the surface of the alloy with prolonging of oxidation time. Consequently, the evaporation rate of the Mo-oxides is greatly reduced, and gathering of Mo atoms begins to occur at grain boundaries when the evaporation rate of Mo oxides is lower than the migration rate of Mo atoms from matrix to grain boundary. Moreover, Mo atoms also may

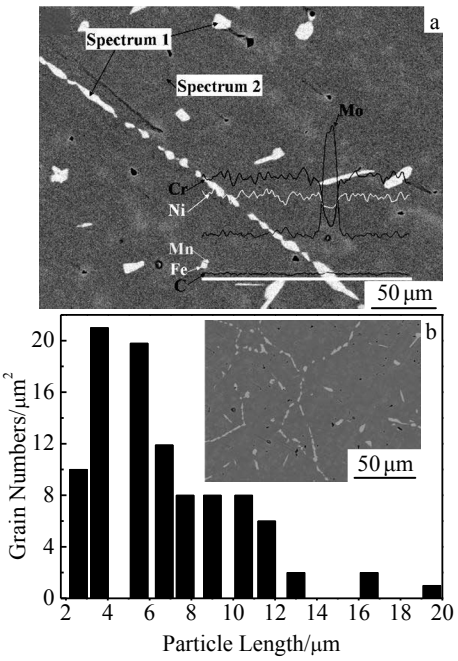

Fig.1 SEM-BSE image and elements line scanning of Cr, Ni, Mo, Mn, Fe, C (a); grain size distribution of second phases (b) (the measured area was about 3.64×10^4 μm^2)