Materials Science & Engineering A 689 (2017) 257–268

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of solution heat treatment on the precipitation behavior and strengthening mechanisms of electron beam smelted Inconel 718 superalloy

Xiaogang You[a,b], Yi Tan[a,b,*], Shuang Shi[a,b], Jenn-Ming Yang[c], Yinong Wang[a], Jiayan Li[a,b], Qifan You[a,b]

[a] School of Materials Science and Engineering, Dalian University of Technology, Dalian 116023, China
[b] Laboratory for New Energy Material Energetic Beam Metallurgical Equipment Engineering of Liaoning Province, Dalian 116024, China
[c] Department of Materials Science and Engineering, University of California, Los Angeles, CA 90095, USA

ARTICLE INFO

Keywords:
Inconel 718
Electron beam smelting
Microstructure
Vickers hardness
Precipitation strengthening

ABSTRACT

Inconel 718 superalloy was fabricated by electron beam smelting (EBS) technique. The effect of solution heat treatment on the precipitation behavior and mechanical properties of EBS 718 superalloys were studied, the strengthening mechanisms were analyzed and related to the mechanical properties. The results indicate that the optimized microstructures can be acquired by means of EBS, which is attributed to the rapid cooling rate of approximately 280 ℃/min. The solution heat treatment shows a great impact on the microstructures, precipitation behavior and mechanical properties of EBS 718 superalloy. The γ`` phase shows an apt to precipitate at relatively lower solution temperatures followed by aging, while the γ` precipitates are prone to precipitate at higher temperatures. When solution treated at 1150 ℃, the γ` precipitates are dispersively distributed in the matrix with size and volume fraction of 8.43 nm and 21.66%, respectively, a Vickers hardness of approximately 489 $HV_{0.1}$ is observed for the aged superalloy. The precipitation strengthening effect of EBS 718 superalloy could be elucidated by considering the interaction between the dislocations and γ``/γ` precipitates. The shearing of γ` is resisted by the coherency strengthening and formation of antiphase boundary (APB), which shows equal effect as weakly coupled dislocation (WCD) model. And for γ``, the strengthening effect is much more prominent with the primary strengthening mechanism of ordering. Moreover, it is interestingly found that the strengthening mechanism of stacking fault (SF) shearing coexists with APB shearing, and SF shearing plays a major role in strengthening of EBS 718 superalloy.

1. Introduction

As a nickel-chromium-iron based precipitation hardening wrought superalloy, Inconel 718 superalloy is widely used from last 5 decades to fabricate the turbine discs, blades, shafts and other high temperature components in aerospace, nuclear power plants and petrochemical industries. The Inconel 718 superalloy is mainly designed for its outstanding strength, superior fatigue and radiation resistance together with good oxidation and corrosion resistance, as well as good processability, welding performance and microstructure stability at elevated temperatures [1,2]. The primary strengthening phases in Inconel 718 superalloy are $L1_2$ ordered face centered cubic (FCC) γ`-Ni_3(Al,Ti) phase, ordered body centered tetragonal (BCT) structured γ``-Ni_3Nb, and a significant amount of orthorhombic $D0_a$ structural δ phase, which is intentionally produced before forging to limit the grain size to about 5–20 µm.

The traditional melting and casting techniques for Inconel 718 superalloy are vacuum induction melting (VIM) plus electroslag remelting (ESR), vacuum induction melting plus vacuum arc remelting (VAR), VIM plus ESR and VAR, and so on. During the recent years, other advanced preparation methods have been also developed for nickel-based superalloys, such as electron beam rapid prototyping [3], powder metallurgy [4], spray forming [5], electron beam freeform fabrication [6], selective laser melting (SLM) and electron beam melting (EBM) [7]. Nevertheless, the metallurgical problems still exist and show a great influence on the performance of superalloys, such as the formation of inclusions whose diameters are larger than the critical flaw size, the reaction of the alloy melt with the crucible materials, the macroscopical and microcosmic defects such as macro-segregation, freckles, white spots and Laves phase as well as previous particle boundaries (PPBs), the controlling of impurities such as O, N, S, P. As a result, it is still challenging to prepare superalloys with excellent metallurgical quality and outstanding properties. Recently, a novel method namely electron beam smelting (EBS) is employed to prepare

* Correspondence to: School of Materials Science and Engineering, Dalian University of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian 116023, China.
E-mail address: tanyi@dlut.edu.cn (Y. Tan).

http://dx.doi.org/10.1016/j.msea.2017.01.093
Received 28 August 2016; Received in revised form 25 January 2017; Accepted 27 January 2017
Available online 02 February 2017

the nickel based superalloys, which has been proved to be of great application prospect in recent research works [8,9]. During the smelting process, the circumstance of high vacuum and local high temperature can effectively promote the degassing reaction of the melt, which facilitates the removal of impurities and inclusions. Furthermore, the previous particle boundary related problems in the above methods can be effectively avoided. Moreover, the water cooled copper crucible can be repeatedly used during the smelting process, preventing the pollution from the crucible materials and reducing the cost.

In this paper, the EBS technology was used to prepare the Inconel 718 superalloy. The microstructures of the traditionally prepared VIM +ESR 718 (hereinafter referred to as standard 718) and EBS 718 superalloy were examined. The effect of solution heat treatment on the precipitation behavior and the mechanical properties of EBS 718 superalloy were investigated, the strengthening mechanisms were analyzed and related to the mechanical properties.

2. Materials and methods

2.1. Materials and electron beam smelting

The compositions of the electron beam smelted 718 superalloy are shown in Table 1. During the smelting process, the vacuum of the smelting chamber and electron beam gun chamber were maintained at $1–4\times10^{-2}$ Pa and $1–3\times10^{-3}$ Pa, respectively. The electron beam current and smelting power were kept constant at 500 mA and 15 kW respectively. The ingot was flip smelted for three times employing the same parameters to ensure the uniform distribution of the elements. After smelting, the ingot was cooled in vacuum to room temperature. The surface layers were removed before the heat treatment in case of the back diffusion of impurity elements. The compositions of the alloy elements can be well controlled by EBS according to Table 1. Besides, the content of P, S, O, N are far below the required level of nominal Inconel 718 superalloy.

2.2. Heat treatments

The electron beam smelted 718 superalloy was solution treated at various temperatures from 940 to 1150 °C for 1 h and air cooled to room temperature. A two-step standard aging treatment was performed subsequently, namely holding at 720 °C for 8 h followed by furnace cooling to 620 °C with the cooling rate of 50 °C/h, and holding at 620 °C for 8 h before air cooling to room temperature.

2.3. Metallographic preparation

Samples for both metallographic and SEM observation were mechanically grinded and polished, and etched with a solution composed of 4 g $CuSO_4$ +20 ml HCl +1 ml H_2SO_4 +16 ml H_2O. For the TEM analysis, samples were mechanically thinned down to a thickness of about 20–50 μm and then polished. The thin areas with a thickness of several nanometers were obtained employing the argon ion beam thinning technique. X-ray diffraction (XRD) technique with the scanning step size and speed of 0.02° and 2.00°/min was used for phase identification.

2.4. Mechanical characterization

The mechanical performance of EBS 718 superalloy was studied by means of Vickers hardness and room temperature compression tests. The Vickers hardness was examined by using a HV-1000A tester with the load of 100 g for 15 s, each hardness value was the average of at least 10 random indentations. The compression tests were conducted on a Gleeble 1500 thermo-mechanical simulator at room temperature with a strain rate of 0.1/s and to a strain of approximately 0.6, which reflected the conditions experienced by components in typical industrial applications.

3. Results and discussion

3.1. Microstructural aspects

3.1.1. As-cast condition

Fig. 1 shows the SEM microstructures of the as-cast Inconel 718 superalloys. As shown in Fig. 1(a) and (b), both the EBS and the traditional standard 718 superalloys exhibit similar micro-segregation behavior, which is attributed to the solidification partition coefficient difference of the elemental compositions. The segregation coefficients of the elements in EBS 718 superalloy are shown in Table 2, which is defined as the composition in the interdendritic region divided by that of the dendrite cores. The results indicate that the Ti and Nb are inclined to aggregate in the interdendritic areas, whereas Al, Cr, Fe and Mo are more likely to gather in the center of the dendrites. The average secondary dendrite arm spaces (SDAS) of the EBS 718 superalloy and standard 718 are determined to be 28 μm and 46.5 μm, respectively. The SDAS is a significant parameter in characterization of the solidification behavior, which reflects the microstructure refinement and segregation degree. The segregation area between the dendrites will be narrower with smaller SDAS values. Besides, the nonmetallic inclusions and precipitates such as Laves phase and δ phase formed during the terminal solidification stages are more uniformly distributed. According to the research work of Wagner [10], the SDAS value is mainly decided by the local solidification time, which is given by:

$$\lambda_S = 5.5(Mt_f)^{\beta} \tag{1}$$

where λ_S is the space of secondary dendrite arm, M is the ripening coefficient, t_f is the local solidification time, β is an exponent decided by the Ostwald ripening process which is controlled by the volume or interface diffusion. A new equation can be derived when combine the expression of M and t_f [11]:

$$\lambda_S = 5.5\left(\frac{C_0 \Gamma D_L \ln\left(\frac{C_L}{C_0}\right)}{k(C_0 - C_L)}\right)^{1/3} R_c{}^{-\beta} \tag{2}$$

where C_O is the original composition of the alloy, Γ is the Gibbs-Thompson coefficient, D_L is the diffusion coefficient of solute atom in the liquid, C_L is concentration of the solute in the liquid, k is the partition coefficient of solute atom, R_c is the cooling rate. With

Table 1
Chemical compositions of Inconel 718 superalloy (wt%).

Element types	Cr	Mo	Co	C	Al	Ti	Nb	Fe
Nominal	17.00–21.00	2.80–3.30	≤1.00	≤0.08	0.20–0.80	0.65–1.15	4.75–5.50	Bal.
EBS 718	18.050	2.942	0.464	–	0.564	1.010	5.014	18.780

Element types	Si	Ni	Mn	P	S	O	N
Nominal	≤0.35	50.00–55.00	≤0.35	≤0.015	≤0.015	≤0.005	≤0.01
EBS 718	0.066	53.070	0.030	0.010	0.002	0.0001	0.0032