ALLOY MORPHOLOGY UNDER SUPERHIGH SPEED DIRECTIONAL SOLIDIFICATION①

Chu, Shuangjie Li, Jianguo Liu ,Zhongyuan Shi, Zhengxing Fu, Hengzhi
Northwestern Polytechnical University, Xi'an 710072, China

ABSTRACT

This paper explains the principle of a newly developed ZMLMC directional solidification apparatus with a superhigh temperature gradient. With the help of the apparatus, research was done on the change of directional solidification structures of the cobalt based superalloy K10 at superhigh velocities. Relations between the primary and secondary dendrite arm spacings and the cooling rates were investigated. Experimental results show that the primary and secondary dendrite arm spacings of directionally solidified cobalt based superalloys are respectively finer than one fifth and one eighth of those produced by conventional directional soli- dification processes. The primary and secondary dendrite arm spacing which can be decreased by increasing the cooling rate, and the relations between these spacings (λ_1, λ_2) and the temperature gradient (G) and solidfication rate (v) were as follows: $\lambda_1 = 1.428 \times 10^3 (G \cdot v)^{-1}$; $\lambda_2 = 0.132 \times 10^3 (G \cdot v)^{-1}$.

Key words: superhigh speed directional solidification superalloy dendrite arm spacing

1 INTRODUCTION

Superalloys which have been widely used in space travel and aviation industry, are important materials for the manufacture of modern aircrafts, liquid fuel rocket engines and all kinds of gas turbines. All kinds of turbine blades produced with conventional manufacturing technologies have poor lasting strength, anticreep characteristics and mechanical fatigue properties. Therefore, development of superalloy directional solidification technology was began in the United States in early sixties, and the creep and high temperature fatigue properties of superalloys were improved to a certain extent.

Since its appearance in sixties, directional technology has experienced three main developing stages: PD method, HRS method and LMC method. Table 1 describes the main metallurgical parameters of the above three methods. It can be seen that the development of directional solidification technology saught high temperature gradients, thus increasing the cooling rate and improving the directional solidification structures. The three traditional directional solidification methods, however, acquired the coarse and large-sized dendrite structures with slanting dendrites and serious dendrite segregation, which limited the further improvement of the properties of superalloys. The research[1, 2, 3] has shown that fine dendrite structures are beneficial to the improvement of the lifetime and plastic properties of the superalloy. Increasing the cooling rate of directional solidification will refine the dendrite, decreasing dendrite segregation. However, because of limited laboratory equipment, these days, investigations on directional solidification technology are generally limited to

①The project was supported by China National Natural Science foundation; manuscript received April 1, 1992

conditions of lower temperature gradients and slower cooling rate[4]. This paper, based on the use of the latest superhigh temperature gradient directional solidification apparatus, has increased the cooling rate from below the traditioal 1 K / s to over 30 K / s, and used to research the changing rule of the dendritic structures of cobalt based superalloys under superhigh speed directional solidification, aimed at seeking new ways to improve the mechanic properties of the directionally solidified superalloy.

Table 1 Metallurgical parameters of three directional solidification methods

solidification parameters	PD method	HRS method	LMC method
temperature gradient / K · cm^{-1}	7~11	26~30	73~103
solidification rate / cm · h^{-1}	18~12	23~27	53~61
cooling rate / K · h^{-1}	90	700	4700

2 DIRECTIONAL SOLIDIFICATION APPARATUS WITH SUPERHIGH TEMPERATURE GRADIENT

Fig. 1 shows the principle of the ZMLMC (zone melting and liquid metal cooling) directional solidification apparatus, which combines the melting of high frequency induction zone and the cooling of liquid metals. The solidification rate (v) may be continually adjusted from 0.006 mm / s to 10 mm / s. The temperature gradient at the forward position of the liquid-solid interface and the cooling rate come up respectively to 1,300 K / s and over 30 K / s.

3 EXPERIMENTAL

The chemical composition of the cobalt based superalloy K 10 used in the experiment was as follows (wt. −%)

C	Si	Mn	Cr	Ni	W	Mo	Fe	Co
0.15	0.69	0.23	27.6	4.1	0.26	4.7	2.3	balance

From the K10 alloy differential heat analysis curve used in the experiment, it is know that the crystallization temperature spacing is very wide (70 K)[5]. The dendrite develops under general cast state, and the straight pillar dendritic structure can only be obtained with higher temperature gradients.

Using dia. 8 mm × 100 mm alloy test sample casted in vacuum melt, experiments on directional solidification at different cooling rates have been made on the ZMLMC directional solidification apparatus. The test samples were processed into thin sections and viewed under optical microscope, and the primary and secondary dendrite arm spacings were measured on the IBS−1 picture analysis apparatus. To ensure the precision of the measurement, each dendrite arm spacing was measured from the average of more than 100 samples.

The temperature gradient at the forward position of the liquid-solid interface was measured with a double platinum rhodium thermo- couple connected to a 3056 vertical platform type Line-Drawing Recorder.

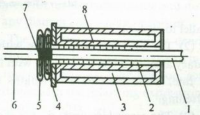

Fig. 1 Schematical diagram of ZMLMC directional solidification apparatus

1—Specimen; 2—induction coil; 3—insulator; 4—cooling water; 5—liquid metal; 6—withdrawal rod; 7—crucible; 8—melting zone

4 RESULTS AND DISCUSSION

Fig. 2 shows the directional solidification structure of the superalloy K10 at different solidification rates with the following main characteristics.

(1) The primary arms are straight and

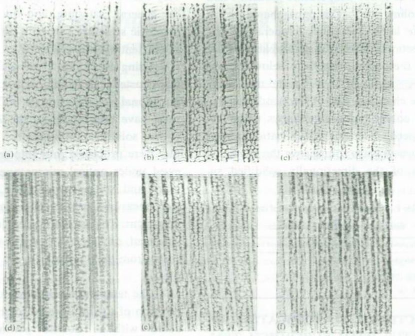

Fig. 2 Superfine column structures of directionallg solidified cobalt based superalloy at different growth rates (× 160)
(a)—$v = 365\ \mu m / s$; (b)—$v = 455\ \mu m / s$; (c)—$v = 629\ \mu m / s$;
(d)—$v = 800\ \mu m / s$; (e)—$v = 917\ \mu m / s$; (f)—$v = 1,030\ \mu m / s$

parallel to each other;

(2) The side arms degenerate with no secondary arms and increase in size with the cooling rate, while the side arm lengths tend to shortening;

(3) The secondary arms do not distplay a distinct coarsening process when the solidification rate is greater than 700 $\mu m / s$;

(4) The dendrite structures are superfine (see data in Table 2). In comparison with typical data on the structure size ($\lambda_1 > 120\ \mu m$, $\lambda_2 > 40\ \mu m$), from HRS method, its primary and secondary dendrite are as fine respectively over five times and eight times.

This change of cobalt base superalloy K10 directional solidification structure is similar to the solidification stūructure by Mirohnichenko[6]. It may be attributed to the high temperature gradient and the rapid directional solidification speed.

From the principle figure of the ZMLMC directional solidification apparatus, it can be seen that forced induction heating makes the solid-liquid interface stay a little high on the cooling alloys liquid upper surface during the whole process, ensuring the direction of heat flow at the interface of liquid and solid will be coincident with the direction of "drawing and pulling". In addition, the high temperature gradient is beneficial to the acquisition of straight pillar dendrite structures. In this experiment, the cooling rate of directional solidification was more than one hundred times that of traditional directional solidification. Thus highly superfine dendrite structures resulted. Meanwhile, since the development of side arms and the coarsening process require time and space, the rapid solidification rate shortens the time of zone solidification, and decreases the length and width of the paste area[7]. The development of side arms is thereby limited, and the coarsening process does not have enough time to proceed.

Table 2 shows the results measured of dendrite arm spacings in the superhigh directional solidification range. The primary and secondary dendrite arm spacings decrease with increasing the cooling rate of directional solidification (Fig. 3), acting in accordance with the following relations.

$$\lambda_1 = 1.428 \times 10^3 (G \cdot v)^{-1};$$
$$\lambda_2 = 0.312 \times 10^3 (G \cdot v)^{-1}$$

In those expressions, λ_1 and λ_2 indicate the primary and secondary dendrite arm spacings. G and v represent the temperature gradient and solidification rate.

Table 2 The measure data of G_1, λ_1, λ_2 and $R \cdot G$ under different direction solidification rate condition.

v / μm · s^{-1}	365	558	629	870	930	1087
G_1 / K · cm^{-1}	111.4	806.5	763.1	699.1	495.2	349.6
λ_1 / μm	34.5	32.4	30.0	23.7	32.0	37.2
λ_2 / μm	7.7	7.0	6.4	5.0	6.8	8.1
$V \cdot G$ / K · s^{-1}	40.57	45.00	47.97	60.82	46.05	38.00

There interdependent relations between the primary and secondary dendrite arm spacings and the cooling rates were decided synthetically from the alloy properties and solidification parameters. In this experiment, because of the high temperature gradient and the small initial values of the primary and secondary dendrite arm spacings, the dendrite coarsening process could not keep pace with the increase in the solidification rate. The magnitudes of the primary and secondary dendrite arm spacings depend upon the initial wave length of the turbulence. Therefore, the primary and secondary dendrite arm spacings decreased respectively from 37 μm and 8 μm to 24 μm and 5 μm with the increase of dendrite solidification cooling rates from 30 K / s to 60 K / s.

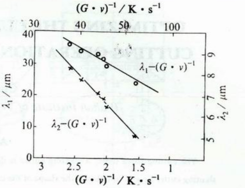

Fig. 3 Primary and secondary dendrite spacings (λ_1, λ_2) vs temperature gradient (G) and solidification rate (v)

5 CONCLUSION

(1) Under conditions of superhigh speed directional solidification, the primary and secondary dendrite arm spacings of the cobalt based superalloy K10 are respectively finer than one-fifth and one-eighth of those formed by conventional HRS method directional process, dendrite structures are superfine, the side arms degenerate with no secondary arms and do not display any distinct coarsening processes.

(2) The primary and secondary dendrite arm spacings decrease with the increases in the cooling rate of directional solidification, acting in accordance with the following expressions.

$$\lambda_1 = 1.428 \times 10^3 (G \cdot v)^{-1}$$
$$\lambda_2 = 0.312 \times 10^3 (G \cdot v)^{-1}$$

REFERENCES

1 Li, Jianping. Master thesis, Northwestern Polytechnical University. 1985.
2 Feng, Feng. Master thesis, Northwestern Polytechnical University. 1989.
3 Lin, Dongliang, Yao, Deliang. Acta Metallurgica Sinica, 1979, 15 (2): A177.
4 Huang, Songhui. Material Report, 1984, (8): 11.
5 Liu, Jiaju, *et al.* Papers Collection of Cast Superalloy, 1986, 16.
6 Miroshnichenko, I. S. Journal of Crystal Growth, 1979, 11:344.
7 Li, Jianguo *et al.* Acta Metallurgica Sinica, 1990, 26 (4): A309.