

# Effects of Cooling Rate on Strength and Microstructure of Powder Metallurgy Superalloys

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## Article Info

### Article history:

Received Jan 19<sup>th</sup>, 2017

Revised Aug 19<sup>th</sup>, 2017

Accepted Oct 18<sup>th</sup>, 2017

### Keyword:

Powder Metallurgy

Cooling Rate

Superalloys

## ABSTRACT

The excellent mechanical properties of powder metallurgy superalloys strongly depend on the microstructure, grain size, morphology, and size distribution of the  $\gamma'$  precipitates. In this study, the effects of cooling rate on strength and microstructure of powder metallurgy superalloys were investigated. Articles were reviewed about this topic and they all were evaluated. Different types of powder metallurgy superalloys such as FGH4096, U720LI, UDIMET 500, MAR-M247, K465, IN738LC, Rene88DT, CM247LC and K5 were selected for this study. These materials were tested in different parameters (temperature and time) and different cooling rates were applied. Test results showed that cooling rate has considerable effects on strength and microstructure of powder metallurgy superalloys. It was observed that the strength increased by the increment of cooling rate. Also, almost homogeneous microstructure was obtained at high cooling rate.

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## 1. Introduction

The excellent high temperature performance of a nickel-based powder metallurgy alloy depends most often on strengthening  $\gamma'$  precipitates. To increase the strength and flexibility of the alloy by heat treatment it is necessary to control the amount, size, morphology and distribution of the  $\gamma'$  phase [1]. In general, the volume percentage of the  $\gamma'$  phase is about 35% to 60% in the high-alloy superalloy. The ratio  $\gamma_c'$  of the cooling  $\gamma'$  precipitates formed during the cooling process exceeds 60%, and therefore examination of  $\gamma_c'$  precipitation behaviors at various cooling conditions is one of the important baseline investigations to increase the temperature ability. [2]. The grain boundaries are weak bonds in the superalloys and easily become rupture at high operating temperatures due to defects in the microstructure. Some carbides and  $\gamma'$  particles as boundary precipitants have significant effects on the high temperature creep resistance and plasticity of nickel-based superalloys. For this reason, examining the morphology and component of the micro-phase near the grain boundaries is a very important issue to strengthen the grain boundaries [2].

## 2. Discussion

Tian and et al. examined the effect of cooling rate on cooling  $\gamma'$  precipitation behavior in nickel-based powder metallurgy superalloy (FGH4096). Chemical composition of the alloy is given in Table 1. The samples were dissolved at 1150 °C for 5 minutes and then cooled to room temperature at different controlled cooling rates.

Experimental conditions are shown in Table 2. The cooling rate plays a crucial role in controlling the amount, size, morphology and distribution of cooling  $\gamma'$  precipitates. The mean sizes of the secondary and tertiary  $\gamma'$  precipitates were inversely correlated with the cooling rate. The shape of the secondary  $\gamma'$  precipitates within grain changes from butterfly like to spherical with cooling rate. However, regardless of the cooling rate, all the tertiary  $\gamma'$  precipitates formed are spherical. The cooling rate has a significant effect on the precipitation behavior of the  $\gamma'$  phase at the grain boundaries and the apparent extent of the grain boundaries; the higher the cooling rate, the narrower the visibility of the grain boundaries [2].

Mao et al. investigated cooling precipitation and strengthening in powder metallurgy superalloy. The excellent mechanical properties of powder metallurgy superalloys depend on the microstructure such as grain size, morphology and size distribution. The microstructure is determined in turn by heat treatment quenching and then aging. Experimental conditions are shown in Table 2. To investigate the effect of quenching, two types of quenching methods (continuous cooling and interrupted cooling) were used to produce different cooled microstructures in the UDIMET 720Li (U720LI) alloy. Chemical composition of the alloy is given in Table 1. In continuous cooling tests, the tensile strength increased linearly with the cooling rate. Interrupted cooling tests have shown that  $\gamma'$  growth is a linear function of decreasing temperature for a given cooling rate. A non-monotonic decay of the tensile strength against the interrupt temperature has been discovered [1]. Tian et al. applied two cooling schemes (continuous cooling and interrupted cooling tests) to investigate the cooling  $\gamma'$  precipitation behavior in the powder metallurgy superalloy FGH4096. Chemical composition of the alloy is given in Table 1. The maximum tensile strength of the samples was tested under various cooling conditions. Experimental conditions are shown in Table 2. The average sizes of the secondary and tertiary  $\gamma'$ -precipitates were obtained between the strength and the cooling rate. The results show that there is an opposite correlated between the average sizes. Interrupted cooling tests show that the mean size of secondary  $\gamma'$  precipitates increases as a linear function of the cutting temperature for a constant cooling rate of 24 °C/min. The ultimate tensile strength of the alloy increases with increasing cooling rate, but it first decreases and increases with decreasing temperature caused by the third  $\gamma'$  precipitate [3].

Table 1: Chemical composition of alloys (wt %)

	<b>FGH409 6</b>	<b>U720L I</b>	<b>UDIME T 500</b>	<b>MAR- M247</b>	<b>K465</b>	<b>IN738L C</b>	<b>Rene88D T</b>	<b>CM247L C</b>	<b>K5</b>
				Balanc e	Balanc e				Balanc e
<b>Ni</b>	Balance	Balance	Balance			Balance	55.63	Balance	
<b>Cr</b>	16.04	16.35	17.9	4.43	8.30	16.49	18.02	8.09	10.3
<b>Co</b>	12.70	14.75	17.2	9.08	9.45	8.72	13.00	9.35	10.2
<b>W</b>	3.98	1.3	-	7.62	9.85	3.36	1.21	9.41	5.1
<b>M o</b>	3.84	3.02	4.00	2.02	1.78	1.90	2.48	0.52	3.96
<b>Nb</b>	0.72	-	-	1.00	0.90	0.88	0.46	-	-
<b>Al</b>	2.18	2.46	-	5.72	5.56	3.26	4.45	5.51	5.54
<b>Ti</b>	3.71	4.99	3.00	-	2.38	3.23	4.74	0.82	2.62
<b>C</b>	0.028	0.025	0.11	0.012	0.14	0.06	-	0.075	0.137
<b>Zr</b>	0.04	0.035	-	-	-	0.04	-	-	-
<b>B</b>	0.0095	-	-	-	-	0.08	-	-	-
<b>N</b>	0.0022	-	-	-	-	-	-	-	-
<b>S</b>	-	0.005	-	-	-	-	-	-	-
<b>Fe</b>	-	0.06	2.1	-	-	-	-	-	-
<b>Re</b>	-	-	-	2.02	-	-	-	-	-
<b>Ta</b>	-	-	-	6.74	-	1.63	-	3.24	-
<b>Hf</b>	-	-	-	0.10	-	-	-	1.53	-

Table 2: Experimental conditions of superalloys

Alloys	Temperature (°C)	Time (min)	Cooling Rates (°C/min)					
<b>FGH4096</b>	1150	5	24	84	258	648		
<b>U720LI</b>	1175	5	11	27	55	110	167	800
<b>UDIMET500</b>	1080	240	3.85	35.4	49.8	90.35	129.5	186
<b>IN738LC</b>	1120	120	36	48	66	-	-	-
<b>Rene88DT</b>	1124	240	24	280	300		-	-
<b>IN738LC</b>	1120	120	11	72	98	247	368	-
<b>CM247LC</b>	1230	120	81	125	168	-	-	-

Sajjadi et al. investigated the effect of cooling rate on microstructure and mechanical properties. For this purpose, after making a partial solution for 4 hours at 1080 °C on the samples of UDIMET 500. Experimental conditions are shown in Table 2. Chemical composition of the alloy is given in Table 1. The microstructures of the samples were examined using optical and electron microscopy. As a result, it was determined that the volume of  $\gamma'$  precipitates decreased with increasing cooling rate. Thus, as the cooling rate increases, homogeneity is observed in the microstructure. It is observed that the increased cooling rate increases the strength but decreases the ductility [4]. Zhang et al. investigated the development of solidification cooling rate microstructures in Ni-based superalloy using conventional casting, injection casting and melt bending methods. MAR-M247 nickel-based superalloy was selected as material. Chemical composition of the alloy is given in Table 1. The sample was dissolved at a temperature of 1273 K for 5 min. Experimental conditions are shown in Table 3. As a result, irregular structures decreased as the cooling rate increased. It has been found that the interspaces of  $\gamma'$  precipitates in the cell structure reduced [5].

Table 3: Experimental Conditions of superalloys

Alloys	Temperature (K)	Time (min)	Cooling Rates (K/min)					
<b>MAR-M247</b>	1273	5	0.72	2.1	9	39	75	870
<b>K465</b>	1483	240	12	120	612	-	-	-
<b>MAR-M247</b>	1633	5	15	60	300	600	-	-

Pei et al. investigated the effect of cooling rate on the microstructure and mechanical properties of K465 superalloy. The chemical composition of K465 is given in Table 1. For this purpose, samples were dissolved at 1483 K for 4 hours. Experimental conditions are shown in Table 3. As a result, as the cooling rate increased, the size of the  $\gamma'$  precipitates decreased and the mechanical properties of the samples increased. It has also been found that the coarse  $\gamma'$  particles are greatly influenced by the cooling rate of the shape and volume fraction [6].

Kavoosi and colleagues investigated the effect of cooling rate on the microstructure and mechanical properties of the IN738LC superalloy. Chemical composition of the alloy is given in Table 1. For this purpose, it was dissolved for 2 hours at 1120 °C. Experimental conditions are shown in Table 2. As a result, as the cooling rate increased, the size of the  $\gamma'$  precipitates decreased and the mechanical properties of the samples increased. It has also been found that the shape and volume fraction of the unified  $\gamma'$  particles are greatly reduced by the effect of the cooling rate [7].

Singh et al. investigated the effect of cooling rate on the development of multiple generation  $\gamma'$  precipitates of Rene88DT superalloy. The chemical composition of Rene88DT is given in Table 1. For this purpose, it was dissolved for 4 hours at 1124 °C. Experimental conditions are shown in Table 2. Continuous cooling at a very high rate after dissolving in the single gamma phase results in a high degree of nucleation and a monomodal size distribution with non-equilibrium compositions. A relatively slow cooling rate (24 °C/min) Resulting in a multimodal size distribution; the larger first generation primary precipitates exhibit near-equilibrium composition, while the smaller-scale secondary  $\gamma'$  precipitates exhibit non-equilibrium composition [8].

Milenkovic et al. examined the effect of cooling rate on the microstructure of MAR-M247 superalloy. The chemical composition of MAR-M247 is given in Table 1. The samples were dissolved at about 1633 K for 5

min. Experimental conditions are shown in Table 3. MAR-M247 showed cellular (15 K/min) and dendritic (60, 300 and 600 K/min) microstructures. It has been determined that the microstructures also change with the cooling rate.  $\gamma/\gamma'$  matrix with carbides and  $\gamma/\gamma'$  eutectic at 15 K/s,  $\gamma/\gamma'$  matrix with carbides at 60 K/min, and  $\gamma/\gamma'$  matrix with carbides and  $\gamma/\text{MC}$  eutectic at 300 and 600 K/min. Furthermore, it has been observed that the range of secondary dendritic arms decreases and the hardness increases as the cooling rate increases [9].

Behrouzghaemi and Mitchell examined the effect of cooling rate on the microstructure of IN738LC superalloy. The chemical composition of IN738LC is given in Table 1. The samples were dissolved at about 1120 °C for 2h. Experimental conditions are shown in Table 2. As the cooling rate decreases, the  $\gamma'$  solid state shows morphological instability and the  $\gamma'$  size shrinks as the cooling rate decreases. The shape changes observed in this study revealed the effect of the cooling rate on the disturbances between  $\gamma$  and  $\gamma'$  [10].

Mehta et al. examined the effect of cooling rate on the microstructure of CM247LC superalloy. The chemical composition of CM247LC is given in Table 1. The samples were dissolved at about 1230 °C for 2 h. Experimental conditions are shown in Table 2. As a result, as the cooling rate increased, the size of the  $\gamma'$  precipitates decreased and the mechanical properties of the samples increased [11].

### 3. Conclusion

The cooling rate plays a very important role in controlling the amount, size, morphology and distribution of cooling  $\gamma'$  precipitates. The average sizes of the secondary or tertiary  $\gamma'$  precipitates are inversely correlated with the cooling rate. The shape of the secondary  $\gamma'$  precipitates in the grain varies from butterfly like to spherical with the cooling rate. However, all the tertiary  $\gamma'$  precipitates formed, irrespective of the cooling rate, are spherical.

Cooling rate has an important effect on the precipitation behaviors of  $\gamma'$  phase at grain boundaries and the apparent width of grain boundaries; the higher the cooling rate, the narrower is the apparent width of grain boundaries. As the cooling rate increased, the size of the  $\gamma'$  precipitates decreased and the mechanical properties of the samples increased. It is observed that the increased cooling rate increases the strength.

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