

Effect of carbon on the casting properties and mechanism of superalloy K4169

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Abstract: In order to obtain the content of C element which is most beneficial to the castability of K4169 alloy within the range of navigation marks, the effects of trace element C on the solidification characteristic temperature, specific heat, viscosity and other physical parameters of superalloy K4169 were measured through practical experiments. With the increase of C element content, the solidus temperature remained basically unchanged, the liquidus temperature decreased, and then the solidification temperature range decreased, which was beneficial to the improvement of castability. The measured physical parameters are imported into ProCAST simulation software, and the fluidity and porosity area percentage of alloys with different C content are actually simulated and calculated. Four kinds of alloys with different C content were tested by a self-designed spiral fluidity test model. The results showed that with the increase of C content, the fluidity first increased and then decreased. When the C content was 0.06%, the fluidity was the best, and the percentage content of loose area was the lowest, which was consistent with the actual simulation results.

Keywords: K4169 superalloy; Carbon content; Thermophysical parameters; liquidity; shrinkage porosity

1 Introduction

K4169 is a precipitation strengthened nickel-base superalloy, with γ "phase as the main strengthening phase and γ' phase as the auxiliary strengthening phase. Due to its excellent corrosion resistance, oxidation resistance and excellent mechanical properties as well as excellent structural stability in the temperature range of -253°C to 650°C, it is now widely used in aerospace and marine structural components, such as turbine engine cases, impellers and other complex structural parts^[1-5]. With the rapid development of advanced aero-engines and the improvement of thrust-to-weight ratio requirements, the quality of complex structural parts of aero-engines has been put forward with higher requirements^[6-7]. However, for superalloy K4169, the range of solidification temperature is wide and the degree of alloying is high^[8], and defects such as under-pouring, segregation and porosity are easy to occur in the manufacturing process of complex structural parts, which greatly reduces the yield and service performance of structural parts.

The range of navigation mark composition of

superalloy K4169 is wide, and at present, the alloy is mostly melted with median composition. Considering the characteristics of the alloy in the casting process, this study optimizes its casting properties by regulating the content of trace elements. Regarding the effect of trace elements on superalloys, for example, X. L. et al.^[9] investigated the effect of trace elements B and C on the fracture toughness of IN718 superalloy at room temperature and 650 °C, respectively. Benhadad S et al.^[10] investigated the effect of segregation behavior of trace elements B and C on the mechanical and welding properties of superalloys. W J Zhang et al.^[11] investigates the effect of trace element C content on the mechanical properties of superalloy IN7178. However, researchers at home and abroad mostly focus on the influence of trace elements on the microstructure, weldability and mechanical properties of the alloy, and there is little research on casting technology, at present.

The castability of superalloys is not only related to the casting process, but also related to the physical properties of the alloy itself^[12]. This experiment casting process are used in the same process

parameters, so that the influence of process parameters on the casting properties of the alloy can be disregarded. The change of trace elements in superalloys will cause the changes of physical properties of the alloys, including solidification characteristic temperature, viscosity, surface tension, enthalpy, etc.^[13], thus affecting the castability of superalloys. However, most researchers have obtained the determination of the physical parameters of alloys through thermodynamic simulation calculations such as JmatPro and Thermo-Calc^[14-16], and then studied the influence of trace elements on the physical parameters, so as to study the influence of physical parameters on the casting properties of superalloys.

This study utilizes the existing alloys to carry out actual testing of alloy physical property parameters, so as to obtain the real effect law of physical parameters. The actual physical parameters are then imported into the ProCAST simulation software to obtain the actual simulation results of trace element C on the fluidity and shrinkage defects of high temperature alloy K4169. The actual fluidity of superalloys with different C content was tested by using the self-designed spiral fluidity test model with equal cross section, and the micro-porosity statistics were made by sampling in the spiral section of the alloy, and the influence law of trace element C on the casting properties of superalloy K4169 was obtained. Finally, the content of C, which is most beneficial to the casting performance of K4169 alloy, is obtained within the range of navigation marks.

2 Materials and methods

In this experiment, the content of carbon was regulated to be 0.02%, 0.04%, 0.06 and 0.08% respectively within the standard range, all other alloy compositional group elements are taken as median values. And the above four K4169 mother alloy ingots conforming to the aviation standard were obtained by using the vacuum induction melting furnace for combining and melting, and the content of carbon in the actual mother alloy ingots is shown in Table 1.

Tab. 1 Actual content of trace element C (wt.%)

Alloy	1	2	3	4
Target	0.02	0.04	0.06	0.08
Actual	0.028	0.048	0.065	0.086

The fluidity of the alloy is closely related to the physical parameters of the alloy itself. The characteristic solidification temperature, phase transformation characteristic temperature, specific heat and enthalpy of K4169 alloy with different carbon contents are actually measured by using the STA-449F3 differential scanning calorimetry (DSC) analyzer of Germany Nech Company^[17-18]. The DSC test sample is a cylindrical sample with a diameter of 3mm and a thickness of 1 mm. Firstly, the sample is heated from room temperature to 1000 °C at a heating rate of 20 °C/min, and then heated to 1400 °C at a heating rate of 10 °C/min, and then cooled to 1000 °C at a cooling rate of 10 °C/min, and then cooled to room temperature with the furnace. The DSC test process is carried out in an alumina crucible with high purity argon atmosphere.

Alloy mobility simulation tests are conducted by ProCAST software. The self-designed equal cross-section spiral test model is imported into ProCAST simulation software for mesh delineation, setting of material parameters and process parameters. The actual measurement results of the above-mentioned alloy thermophysical parameters-temperature change trend are imported into ProCAST to replace the original thermophysical parameter data of the alloy in the software library, and other untested parameters still use the data in the database. Under the condition that other parameters are unchanged, each group of experiments only changes the alloy composition and the measured thermophysical parameters, and obtains the influence law of the change of trace element C content on the flow properties of superalloy K4169.

The alloy mobility test utilizes an independently designed equal cross-section spiral test model, as shown in Figure 1. The maximum test length of alloy fluidity is 980mm, the height of helix is 10mm and the thickness is 3 mm. In order to ensure the consistency of the experiment, the fluidity test are taken 1Kg master alloy material. Firstly, the fluidity test formwork is put into a box furnace, preheated to 800 °C and kept for 4 hours, and then heated to 980 °C at a heating rate of 10 °C/min and kept for more than 2 hours. When the vacuum induction melting furnace is vacuumized to 10⁻²Pa, the alloy is heated at a lower melting power to make it in a red-hot state, and then the melting power is increased to make the alloy melt evenly. After that, the melting power was adjusted to

make the melt temperature reach 1450°C, and the alloy liquid was poured into the preheated fluidity test model at the pouring speed of 0.5 kg/s. When the alloy liquid is poured into the flowing mold shell, the temperature decreases, and the superalloy liquid stops flowing, thus completing the filling process of the flowing model. The flow test model after filling is taken out, and the length of spiral section after alloy filling is counted respectively, and the flow performance of alloy is reflected by the equal cross-section spiral length of alloy filling.



Fig. 1 Liquidity test model

Statistical samples of alloy shrinkage porosity area were sampled at the riser, 30mm spiral of riser and 1/2 spiral length of spiral test model, respectively. The shrinkage statistics samples were mechanically polished after fine grinding with sandpaper (80#-2000#) until the surface of the samples was bright and without obvious scratches, and the shrinkage defects were observed under an optical microscope. Image-Pro software was used for the statistics of the shrinkage area to obtain the influence law of trace element C on the shrinkage area of superalloy K4169.

3 Results

3.1 Effect of carbon content on thermophysical parameters

With consistent casting process parameters, trace element C affects the casting properties of the alloy mainly by influencing the physical properties of the alloy, among which the characteristic temperature range, specific heat, surface tension and viscosity will have a greater impact on the casting performance of

the alloy. The compositions of the four alloys with different C contents were imported into the JmatPro software simulation, respectively, and the physical parameters such as solidification temperature interval, specific heat and surface tension were calculated for the four K4169 alloys with different C contents, and the results are shown in Fig. 2.

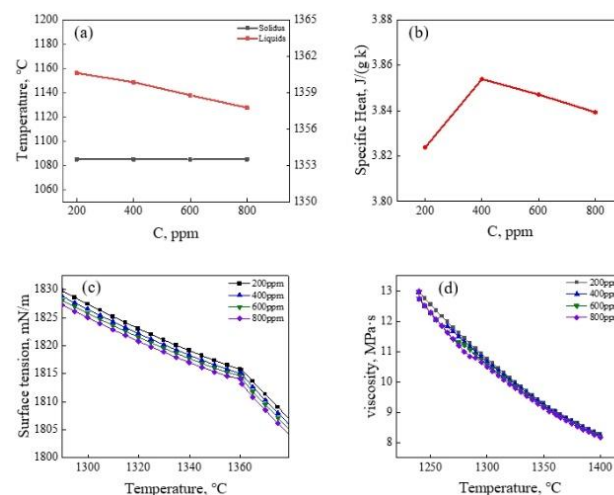


Fig. 2 Physical parameters obtained from JmatPro simulations:

(a) Solidification characteristic temperature (b) Specific heat (c) Surface tension (d) Viscosity

According to the simulation results of JmatPro, with the increase of C content, the liquidus temperature of the alloy decreases, and the solidus temperature remains basically unchanged, so the solidification interval of the alloy decreases. For K4169 superalloy with wide crystallization temperature range, the flow stops when the melt temperature of the alloy drops below the liquidus temperature, and the solid phase precipitates out of the liquid^[19]. With the solidification process and the growth of dendrites, the viscosity of alloy liquid increases and the flow rate slows down. When dendrites overlap each other into a continuous network and the pressure of alloy liquid cannot overcome the resistance of this network, the flow of liquid stops. The lower solidification interval of the alloy will make the alloy precipitate a lower content of solid phase during solidification, which will make the internal dendrite lapping temperature of the alloy lower, which will help to improve the fluidity of the alloy.

The specific heat of an alloy is a relatively important parameter for the solidification characteristics of an alloy. For the specific heat of alloy, under the condition of the same mass and degree

of superheat, the larger the specific heat of alloy, the more heat is released during solidification^[20], the longer it will remain in the liquid state, thus improving the fluidity of the alloy. According to the simulation results of JMatPro, the peak specific heat of the four alloys first increases and then decreases, so it is speculated that the fluidity of the alloys also increases first and then decreases.

For the surface tension of the alloying liquid, since the alloying liquid is not wetted with the mold shell, the liquid surface in the thin-walled part of the mold is convex, and the surface tension generates resistance pointing towards the interior of the liquid^[21], resulting in a reduction of the fluidity of the alloy. The simulation results show that the surface tension of the alloy decreases with the increase of C content, and the smaller the surface tension of the alloy, the less the obstacle to the flow of alloy liquid, which is more helpful to improve the fluidity of the alloy.

For the viscosity of alloy liquid, the smaller the viscosity of alloy melt, the more favorable it is for the flow of alloy^[22]. From the calculation results, it can be seen that the viscosity of the alloy liquid gradually decreases with the increase of C content, which is more conducive to improving the fluidity of the alloy.

3.2 Effect of carbon content on fluidity

3.2.1 ProCAST Simulation

The filling simulation of the four alloys with different C content was carried out by ProCAST simulation software. Under the same other conditions, the filling length of the alloy liquid in the self-designed fluidity test model was used as an index to evaluate the excellent fluidity of the alloy liquid. In the simulation, the pouring temperature of the alloy is set at 1450 °C, the mold shell temperature is set at 700 °C, and the casting method is gravity casting. The four alloys were subjected to mold filling simulation experiments respectively and the following results were obtained as shown in Fig. 3. From the results, it can be seen that the flow charging ability of the alloys gradually increases with the increase of C content. The simulated flow charging length of K4169 superalloy was 289 mm at 0.02% C. The simulated charging length of the alloy was extended to 297 mm when the C content was increased to 0.08%, which increased the simulated charging capacity of the alloy by 2.77% under the same conditions.

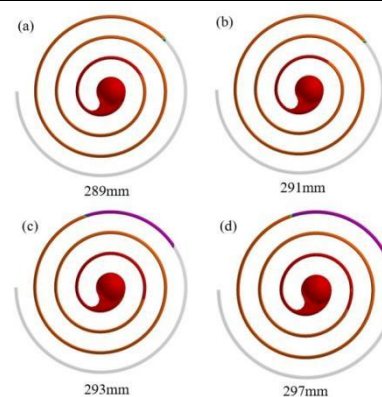


Fig. 3 Results of liquidity simulations (a) 0.02%C (b) 0.04%C (c) 0.06%C (d) 0.08%C

3.2.2 Fluidity performance casting

Four K4169 alloys with different C contents melted in the vacuum induction melting furnace were used for actual casting to verify the law of C content on the flow properties of the alloy, as shown in Fig. 4. The cast specimen was cooled to room temperature, the spiral alloy specimen was removed, and the flow length of this spiral alloy specimen filled was measured to obtain the mobility of the four alloys under the same casting process conditions, respectively. As can be seen from the results in the following figure, with the increase of C content, the spiral length obtained by liquid filling of the alloy first increases and then decreases. When the C content is 0.02%, the filling ability of the alloy is the smallest, and the filling spiral length is 203mm. When the C content is 0.06%, the spiral length of K4169 alloy is the longest, which is 286 mm. Compared with the alloy with 0.02% C content, the fluidity is improved by 40.8%.



Fig. 4 Test results of flow properties of alloys with different C content (a) 0.02%C (b) 0.04%C (c) 0.06%C (d) 0.08%C

According to the above simulation results and the actual casting results comparison can be seen, with the rise of the C content, the flow properties of the simulation results show a gradual increase in the trend, while the actual casting of the flow properties of the first rise and then decline in the trend, when the C content of 0.06, the alloy has the best fluidity properties. Combined with the results of calculating the thermophysical parameters of K4169 alloy with different C contents, it can be seen that only the changes in the thermophysical parameters due to the changes in the alloy composition are considered during the simulation calculations, and therefore, the simulation results coincide with the trends of the thermophysical parameters due to the changes in the C content.

In the actual casting process, the change of C content not only causes the change of thermophysical parameters, but also leads to changes in the content of precipitated phases in the alloy, precipitation temperature, etc., which has a complex effect on the alloy flow properties. According to the actual pouring results, when the content of C is less than 0.06%, with the increase of C content, the fluidity of K4169 alloy becomes more and more excellent. The main reason is that the increase of C content reduces the solidification temperature range of the alloy, reduces the dendrite lap joint temperature of the alloy and delays the time when the alloy stops flowing. Elevated C content also results in a higher specific heat and lower viscosity of the alloy, resulting in an increased flow and filling capacity of the superalloy K4169. However, when the content of C element exceeds 0.06%, the fluidity of K4169 alloy will be reduced, mainly because when the content of C is too high, the carbide precipitation in the alloy melt will increase obviously, too much carbide in the melt will increase the viscosity of the alloy liquid, and too much carbide between dendrites will hinder the flow of the alloy liquid, thus reducing the fluidity of the alloy.

3.3 Effect of carbon content on shrinkage defects

Four spiral K4169 alloy samples were cast, and their cross sections were sampled at the riser, 30mm from the riser and 1/2 of the spiral length. After fine grinding by sandpaper (80#-2000#), they were mechanically polished until the surfaces of the samples were bright without obvious scratches. The shrinkage defects were observed under the optical

microscope, and the results are shown in Figure 5.

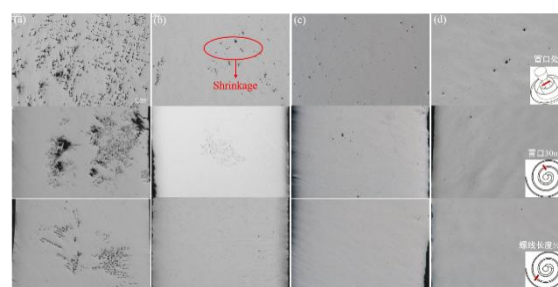


Fig. 5 Effect of C content on shrinkage defects (a) 0.02%C (b) 0.04%C (c) 0.06%C (d) 0.08%C

Percentage of shrinkage area is usually considered to be the proportion of area occupied by shrinkage defects per unit area, which is used to indicate the number of shrinkage defects in a certain location in the alloy, and the percentage of shrinkage area can be expressed as the following equation:

$$\varepsilon = \frac{S_l}{S} \times 100\% \quad (3-1)$$

where ε is the percentage of shrinkage area; S_l is the area where shrinkage occurs at the selected cross section; S is considered to be the total area of the selected cross section.

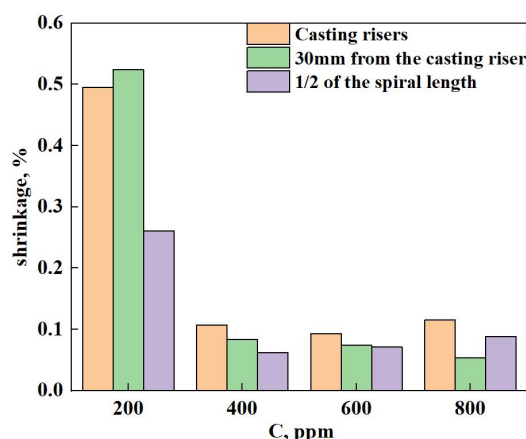


Fig. 6 Effect of C content on the percentage of shrinkage area of shrinkage holes at different locations

The Image-Pro software was used to calculate the percentage of sparse area at each location, and the results are shown in Figure 6. It can be seen from the results that the percentage of shrinkage area in the alloy specimens also shows a decreasing and then increasing trend with the increase of C. When the C content is 0.02%, the shrinkage area ratios at the risers, risers 30mm and 1/2 of the length of the screw threads are 4.95%, 5.24% and 2.61%, respectively, and the average shrinkage area ratio is 4.26%. At 0.06% C content, the alloy has the highest flow-forming ability and the least shrinkage in the alloy, with shrinkage

area percentages of 0.93%, 0.74%, and 0.71%, respectively, and an average shrinkage area percentage of 0.79%, which is a significant reduction in shrinkage area of about 81.5% compared to the alloy with a C content of 0.02%.

Shrinkage defects in alloys are mainly caused by volume contraction during solidification. In the solidification process of the alloy after the completion of the branch crystal overlap, the branch crystals to make up the contraction channel is blocked and the branch crystals between the region of the liquid is insufficient to make the branch crystals can not make up the contraction of the last part of the solidification, which leads to the formation of shrinkage defects. Shrinkage defects in alloy castings reduce the effective area subjected to forces and cause stresses to be concentrated at shrinkage and shrinkage holes, leading to a reduction in the mechanical properties of the alloy.

The probable reason that the elevated C content decreases the percentage of the alloy's spar area is that increasing the C element content when shrinkage and loosening defects are more prevalent results in an increase in the carbide content of the alloy, which can fill the holes between the dendrites to reduce the spar defects by late growth during solidification. While increasing the content of C element at less defects will increase the shrinkage defects in the alloy, the possible reason is that the growth of too much carbide hinders the flow of alloying liquid, which hinders the replenishment and shrinkage effect of the alloying liquid on the internal tiny melting pool, and makes the increase of loosening defects in the alloy.

4 Conclusions

In this paper, we investigated the modulation of the C element content of K4169 alloy within the standard range to optimize the casting performance of the alloy, and obtained the following conclusions:

(1) The content of C element in K4169 alloy is controlled within the standard composition range. With the increase of C element content, the flow filling ability of the alloy first increases and then decreases. When the C content is 0.06%, the spiral length of K4169 alloy is the longest, which is 286 mm. Compared with the alloy with 0.02% C content, the flow filling ability is improved by 40.8%.

(2) The cross-sections at the riser, 30mm of the

riser and 1/2 of the spiral length of the alloy were taken for shrinkage statistics. With the increase of C content, the percentage of porosity in the alloy sample also showed a trend of first decreasing and then increasing. When the C content was 0.06%, the shrinkage porosity in the alloy was the least, and the average shrinkage porosity percentage was 0.79%. Compared with the alloy with 0.02% C content, the shrinkage porosity area was obviously reduced.

(3) In the standard range of regulation of K4169 alloy C element mass percentage of 0.06%, the alloy flow filling ability is the highest, the alloy appears in the smallest area of shrinkage, and the casting performance of K4169 alloy is the best.

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Conflicts of interest:

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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