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Study on creep characteristics of oil film bearing Babbitt

J. M. Wang*[1], Y. W. Xue[1], W. H. Li[2], A. Z. Wei[3] and Y. F. Cao[3]

According to the creep deformation of oil film bearing Babbitt in operation process, the creep test method of Babbitt was put forward, the factors about influencing the results of creep test were analysed, and the creep test research of Babbitt was carried out. The test data were processed, and the creep characteristics of SnSb11Cu6 and SnSb8Cu4 were acquired based on Graham creep equation and the wheat quarts method and global optimisation algorithm. The relationship between creep coefficients and stress has been obtained, and a group of creep curves under different stress has been speculated through calculating stress related indexes. At the same time, the accuracy and reliability of creep deformation of Babbitt were verified through finite element numerical simulation on the test specimens based on ANSYS. Then the creep characteristics of Babbitt of oil film bearing were carried out by finite element numerical simulation.

Keywords: Oil film bearing, Babbitt, Creep test, Creep curve, Creep model, Creep deformation, Creep characteristics, Data extrapolation, Stress related indexes, Numerical simulation

Introduction

Oil film bearing is widely used in important devices in such industries as iron and steel, mining, metallurgy, electrical power, aerospace; its Babbitt is the weakest working section. Generally, when the working temperature of material reaches above $0{\cdot}3T_\mathrm{m}$ (T_m is the melting point of material.), the material will be likely to creep. Babbitt is of low melting point and has good performances such as high load capacity and wear resistance. The commonly used Babbitt of oil film bearing are SnSb11Cu6 and SnSb8Cu4, and their corresponding melting points are respectively 241 and 200°C. When the internal working temperature of bearing rises to 60–90°C, it already reaches the critical temperature for the creep of material, and the micro creep may occur during the working process, which has a negative influence on the lubricating performances and load capacity of oil film and bearing life.[1,2]

Currently, some metallurgical device manufacturers have undergone some research on the creep of Babbitt, e.g. SMS Company has developed new type ULC Babbitt (ultra-low creep). DanOil has developed a kind of oil film bearing with ultra-high strength Babbitt; thus the incidence rate of creep was decreased by 90%. Morgan KLX oil film bearing uses high strength Babbitt (HSB) with good creep resistance performance. However, the above relative research progress is in the technologically blocked state, and no literature can be browsed, so the research on the creep of Babbitt is yet to be worshiped.[3–5] It is very necessary to explore the creep phenomenon on Babbitt of oil film bearing through creep test on it.

As known from literatures, many experts have already done different research on creep, e.g. Wilshire[6] brought forward an experimental method on metallic creep and gave out a method to decrease experimental error through analysing all the influencing factors to the results. Robert[7] gave out a method on how to choose creep model and analysed the extrapolated method of experimental data to Kelvin–Chain based creep model. Cadek[8] analysed the influences of stress and temperature on creep behaviours of material, and illustrated the control mechanism of creep rate. Meanwhile, he gave out the research method on material's creep behaviours with a combination of theory and experiment. Zhang[9] studied the creep performance and mechanism of Mg alloy under high temperature and low stress, and obtained its high temperature creep properties, etc. All the above relative literatures studied creep features of different materials such has iron, steel, Mg and Al. However, till now there has no literature on the creep of Babbitt. Therefore, to fulfill the research blank, this study chose Babbitt as research object, gave out its creep test method through setting the proper insulating time and the loading rate, and further studied creep properties of Babbitt with a combination of scientific data processing method, experiment and FEM numerical simulation.

Experimental

For under 100°C creep test, the accuracy of heating control of the existing creep testing machine cannot meet

[1]School of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China
[2]School of Mechanical, Material and Mechatronic engineering, University of Wollongong, NSW 2522, Australia
[3]Sinopec Lubricating Oil Research and Development Center (Beijing), Beijing 100085, China

*Corresponding author, email wjmhdb@163.com

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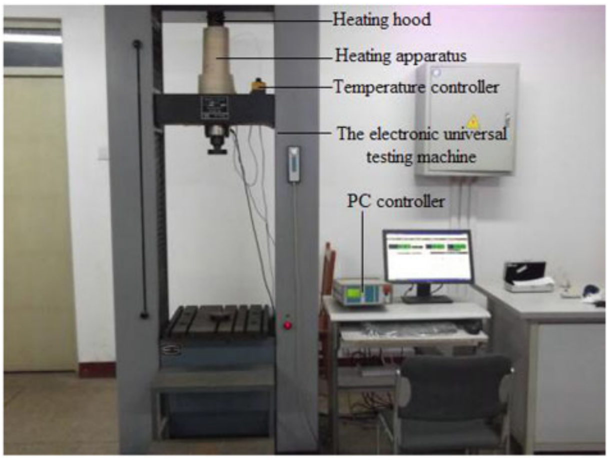


1 Creep test device

2 Specimen for creep test

test standard of creep. Therefore, the Babbitt creep test is done on the reformed WDW-E100D electronic universal testing machine; the accuracy of this device can better meet the requirements of creep test. The actual working temperature of Babbitt that probably produces creep is about 65°C, and work stress of Babbitt is less than 20 MPa. Therefore, the creep experimental temperature was set as 65°C, and the experimental stress were set as 10 and 15 MPa. The heating belt was used to heat the specimen within heating hood to the specified temperature, and then the corresponding programs were compiled into computer to stably control the loading force. YYU-series electronic stretcher was used to measure the specimen. Moreover, the measured deformation was transferred directly to computer control interface through PC controller, and the values were online recorded timely. According to the test demands of National Standard GB/T2039-1997, creep test was done on SnSb8Cu4 and SnSb11Cu6. The test device for creep was shown in Fig. 1. Main chemical compositions of SnSb8Cu4 and SnSb11Cu6 were shown in Table 1, and creep test specimen was shown in Fig. 2.

The steps of Babbitt creep test are listed as below:

- (i) step 1: check all the performances of the testing machine
- (ii) step 2: install the specimen and the extensometer
- (iii) step 3: install the heating equipment
- (iv) step 4: edit the procedures of auto control program
- (v) step 5: end of the test. (Dismantle all the testing machines)

The procedures of auto control program are listed as below:

- (i) step 1: input the initial force as 0·15 kN and the preheated time as 18 000 s^{-1} before heating-up
- (ii) step 2: input the loading rate as 0·002 kN s^{-1} before the stability of load
- (iii) step 3: input the load and holding time when the load is stable
- (iv) step 4: input the protecting program (set the lower limit of the load)
- (v) step 5: input the time increment program (when the test time needs to be prolonged).

Results and discussion

Establishment of mathematical model

The time related polynomial with power exponent has good changing adaptability on creep strain rate in different creep models and can accurately describe the first stage of creep. The constitutive equations of time hardening law can better explain the stable creep rate at the second stage of creep.[5] The study on the creep of Babbitt mainly emphasizes its first and second stage.

On the basis of time hardening law, when the temperature is constant, the relationship between stress, strain, creep rate and time are as below[10]

$$\Phi(\dot{\varepsilon},\sigma,t)=0 \tag{1}$$

where $\dot{\varepsilon}$ is the creep strain rate, σ is the stress and t is the time.

The creep rate is described as follows[10]

$$\dot{\varepsilon}=\sigma^{n}B(t,T) \tag{2}$$

where n is material constant, and $B(t, T)$ is the function relative with temperature and time.

Graham creep model illustrates the creep process with time function $f(t)$ as the basis. The General Graham creep equation uses Graham mathematical model as the basis and integrates the exponent polynomial with time hardening theory. The time function is as below[11]

$$f(t)=\sum a_{i}t^{m_{i}} \tag{3}$$

where a_i is the polynomial coefficient and m_i is the parameter relative to time.

The General Graham creep equation is expressed as[11–13]

$$\dot{\varepsilon}=c_{1}\sigma^{c_{2}}(t^{c_{3}}+c_{4}t^{c_{5}}+c_{6}t^{c_{7}})e^{-c_{8}/T} \tag{4}$$

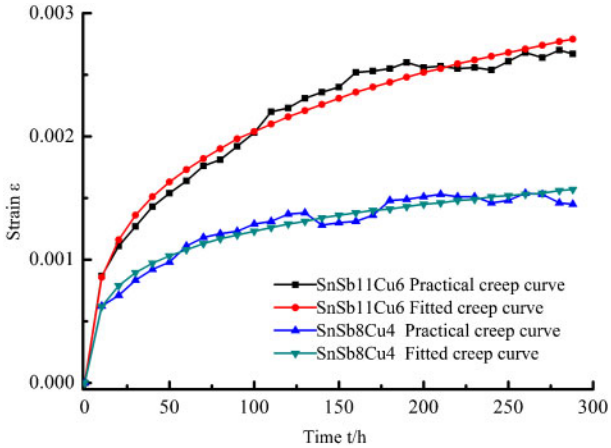
where C_i is creep coefficient (i=1–8), which can be obtained through nonlinearly fitting on the creep test curves, and T is temperature.

Choice of curve fitting algorithm

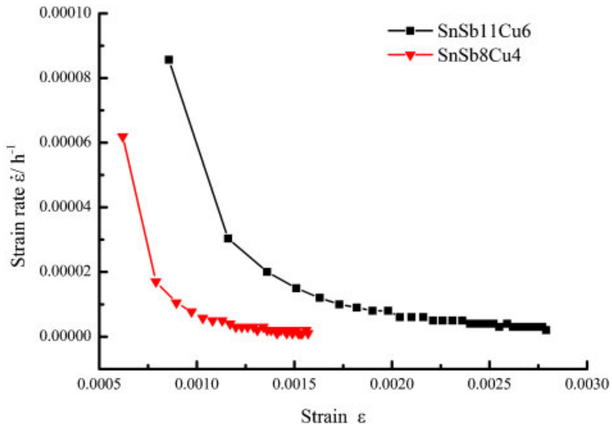
The data were non-linearly fit by Marquardt iteration method,[7] which was the transformation of the regression

Table 1 Main chemical composition of SnSb8Cu4 and SnSb11Cu6

	Chemical composition /%								
Alloy Grades	Sb	Cu	Pb	As	Bi	Fe	Zn	Cd	Sn
SnSb8Cu4	7·0–8·0	3·0–4·0	0·35	0·10	0·08	0·06	0·005	0·05	The other
	10·0–12·0	5·5–6·5	0·35	0·05	0·05	0·08	0·005	0·05	The other



3 Creep curve of Babbitt at 65°C −15 MPa



4 Relationship between strain rate and strain at 65°C −15 MPa

of high order item of Gauss–Newton iteration method, and then the smooth creep curve was obtained. Such method has strong optimized direction of iterative increment and has wide demand on the initial values.[14]

Because of convenient operation and accurate result of 1stOpt in non-linear fit, especially the use of global optimised algorithm and without the need of assigning initial value of variable, as well as the control on the value ranges of variables under the designated boundaries, 1stOpt software[8] was chosen to analyse the test data of Babbitt creep.

Influencing factors on creep test

Influences of temperature fluctuation on creep test

When stress and time are constant, General Graham creep equation can be simplified as below[15]

$$\dot{\varepsilon}=Ae^{-2B/2T} \quad (5)$$

where A and B are constants.

ΔT is the micro temperature change as below

$$\Delta\dot{\varepsilon}=\frac{\partial(Ae^{-\frac{B}{T}})}{\partial T}\Delta T \quad (6)$$

$$\Delta\dot{\varepsilon}=Ae^{-\frac{B}{T}}\frac{B}{T^2}\Delta T \quad (7)$$

Where $\Delta\dot{\varepsilon}$ is variation of creep rate, and ΔT is variation of temperature.

The relative variation rate of creep deformation is as follows.

$$\frac{\Delta\dot{\varepsilon}}{\dot{\varepsilon}}=\frac{B}{T^2}\Delta T \quad (8)$$

As known from equation (8), the relative change rate of creep deformation is positively proportional to the temperature fluctuation and negatively proportional to the square of temperature. Therefore, the load case at a relatively high temperature was suggested for the test so as to ensure the invariant temperature of heating hood.

Influence of temperature fluctuation on measurement accuracy

There was a temperature field varying with time within the heating hood, the temperature of the specimen and the stretcher varied with it. Both would produce relative displacement when their thermal expanding coefficients were different. The displacement would be superimposed into the creep deformation. To decrease such negative influence, the stretching rod used the material with smaller coefficient of linear expansion.[16]

Influence of load fluctuation on creep test

When temperature and time are constant, General Graham equation can be simplified as below

$$\dot{\varepsilon}=P\sigma^Q \quad (9)$$

where P and Q are constants.

When the stress has micro change $\Delta\sigma$

$$\Delta\dot{\varepsilon}=\frac{\partial(P\sigma^Q)}{\partial\sigma}\Delta\sigma \quad (10)$$

where $\Delta\sigma$ is the stress variation.

The relative change rate of creep deformation is described as blow

$$\frac{\Delta\dot{\varepsilon}}{\dot{\varepsilon}}=\frac{PQ}{\sigma}\Delta\sigma \quad (11)$$

As known from equation (11), the relative change rate of creep deformation is positively proportional to the change of stress and negatively proportional to the stress. Therefore, the load should be kept constant, and the vibration should be decreased as much as possible during test procedure.[10]

Analysis on creep curve of Babbitt

On the basis of creep curves of the first and second stages from test data of SnSb11Cu6 and SnSb8Cu4 at constant 65°C and under 15 MPa, and according to Graham creep mathematical model, Marquardt iteration method and global optimisation method were chosen to fit nonlinearly the test data, and then the according creep fit curve was plotted as Fig. 3, from which we can know that:

(i) both Babbitt in operation process will have obvious creep. The creep deformation of SnSb8Cu4 and SnSb11Cu6 are respectively 0·067 and 0·137 mm within 280 h at 65°C −15 MPa, which is likely to decrease the stability of oil film and the capacity of bearing, thus shortening the life of oil film bearing

(ii) as shown in Fig. 4, the plasticity of both Babbitt continuously decreases with the increasing strain and the decreasing strain rate. Such

Table 2 Constant coefficients of creep to SnSb11Cu6

C_1	C_2	C_3	C_5	C_7	C_8
2.67×10^{-11}	4·1502	−1·0017	−0·8051	0·0844	0·0000

phenomenon is called as the strain hardening, which is the major cause of Babbitt creep. The process of Babbitt creep can be summarised as a competitive process of alloy reversion and dislocation multiplication caused by strain hardening.

(iii) in this experiment, the creep curves of both Babbitt are divided into two phases. The first phase is the decelerating creep stage. The creep rate gradually decreases with time, and finally enters into the second phase (steady creep stage). Compared with SnSb11Cu6, the time that SnSb8Cu4 reaches the stable stage is shorter. The reason is that, under the effect of stress, the strain hardening will appear due to the dislocation proliferation within the grain of Babbitt, and the intensified atomic diffusion movement under the effect of temperature results in the reversion phenomenon. When the reversion is balanced with the strain hardening, the alloy reaches the steady creep state.

(iv) as shown in Fig. 3, the creep strain of SnSb11Cu6 is somewhat larger than that of SnSb8Cu4 at the same constant, and the D-value will gradually become larger with time. Compared with SnSb8Cu4, the creep rate of every hour at the first stage of SnSb11Cu6 and its stable creep rate at the second stage are both larger. The creep behaviours of metal and alloy have obvious texture sensitivity, and vary with the chemical compositions, process and heat treatment, etc. The creep features of both Babbitt will be different due to different chemical compositions. The texture of SnSb11Cu6 is Ti based α solid solution, Cu_6Sn_5 and SnSb; the texture of SnSb8Cu4is is Ti based α solid solution and Cu_6Sn_5, during which the Ti based α is soft phase, SnSb and Cu_6Sn_5 are solid phase. The α solid solution of SnSb11Cu6 is more than that of SnSb8Cu4 and has some SnSb, which results in more probability of creep diffusion and creep dislocation. Moreover, compared with SnSb8Cu4, SnSb11Cu6 has larger creep strain and strain rate. Therefore, the creep properties of SnSb11Cu6 Babbitt will be more obvious during the actual operation of oil film bearing.

Extrapolation of creep data of Babbitt

The time for creep test lasts longer. A group of data only represents the creep properties under one load case. The relationship of creep strain with time of the same material is somewhat different under different stress.

Table 3 Variable coefficients of creep to SnSb11Cu6

Stress σ/MPa	Variable coefficient of creep: C_4	C_6
15	24·0194	1.00×10^{-9}
10	30·0000	7.48×10^{-4}

The parameters $C_i(i=1–8)$ in Graham creep model has a certain relationship with the material itself, temperature and stress as shown in equation (12),[11] and the creep coefficient in creep constitutive equation, which is influenced by stress, accounts for only a little proportion. During the creep coefficients in Graham creep equation, only C_4 and C_6 vary larger with stress, and the differential of fitted value of other creep coefficients is very small

$$\lg C_i = a_i + b_i T + c_i\sigma + d_i T\sigma \tag{12}$$

where C_i is creeping coefficient (i=1–8) and a_i, b_i, c_i, d_i are material constants.

Equation (12) is used to build the relationship between creep coefficient and stress as follows[11]

$$C_4 = 10^{(a_4+b_4\sigma)} \tag{13}$$

$$C_6 = 10^{(a_6+b_6\sigma)} \tag{14}$$

where a_4, b_4, a_6 and b_6 are material constants.

According to the test data of SnSb11Cu6 Babbitt at a constant temperature 65°C and under 15 and 10 MPa, the creep coefficients of Babbitt were obtained. Table 2 gave out the creep constant coefficient $C_i(i=1–8)$. The varying coefficients C_4 and C_6 could be got when the constant coefficients were substituted into equation (4) for fitting the creep curve as shown in Table 3. Then the values in Table 3 were used for equations (13) and (14); thus two groups of linear equations can be expressed as below

$$\begin{cases} 24.019373 = 10^{(a_4+15b_4)} \\ 30 = 10^{(a_4+10b_4)} \end{cases} \tag{15}$$

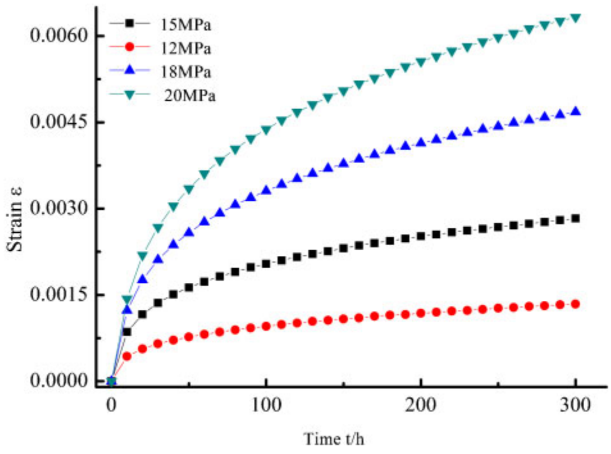
$$\begin{cases} 1\text{e-}9 = 10^{(a_6+15b_6)} \\ 30 = 10^{(a_6+10b_6)} \end{cases} \tag{16}$$

As shown in Table 4, the material constants a_4, b_4, a_6, b_6 can be obtained by equations (15) and (16); thus the creep curves under other stress can be extrapolated.

According to the actual load case of oil film bearing,[17] choosing 12, 18 and 20 MPa as three groups of stress, the creep curves of SnSb11Cu6 under different stress were extrapolated as shown in Fig. 5. The overall tendency of all creep curves is ideal, and the extrapolated result is more accurate. The stress relative index was adopted to extrapolate the creep properties under

Table 4 Stress relative exponent of variable coefficients of creep to SnSb11Cu6

Variable coefficients of creep	C_4		C_6	
Relative exponent	a_4	b_4	a_6	b_6
Value	1·6702	−0·0190	4·5336	−0·7559



5 Creep curves of SnSb11Cu6 under different stress

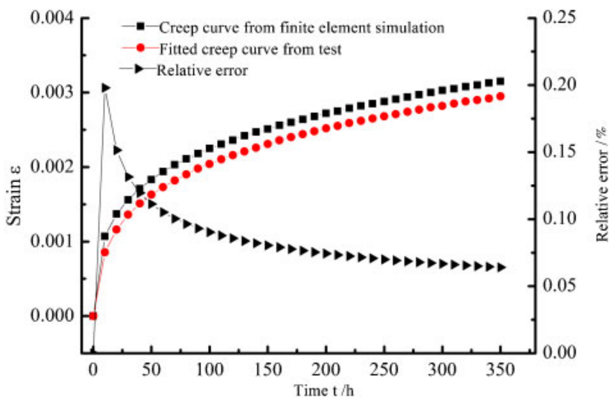
different stress; thus the creep curve under unknown stress could be deduced, and the data blind zone of creep properties under unknown stress could be compensated, which could provide experimental data and theoretical calculating foundation for further analysis on creep properties of Babbitt.

FEM simulation

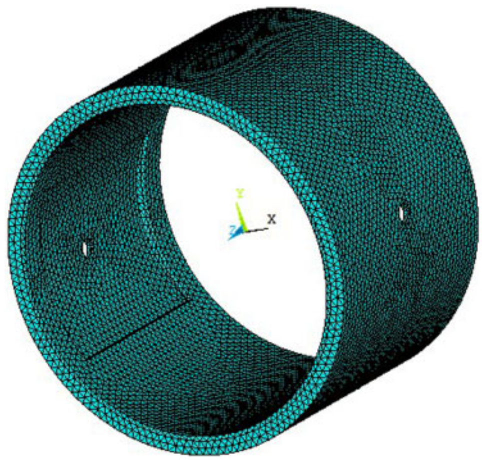
General Graham creep model with higher accuracy was chosen for ANSYS creep analytical simulation, as illustrated in equation (4). The creep coefficient C_i (i=1–8) for calculation in this model used the constant coefficients of SnSb11Cu6 based on the test data of creep, as shown in Table 1. ANSYS was utilised to simulate numerically the SnSb11Cu6 specimen. The comparison of numerical results and test results was used for validating the accuracy and feasibility of ANSYS to calculate the creep of Babbitt.

The specimen for creep test can meet the feature of axial symmetry in geometry, load conditions and boundary conditions. One quarter region of specimen was chosen to build the geometrical model. PLANE183 unit that can analyze creep and build up axisymmetric condition was chosen for meshing the model. Such unit has eight nodes, with quadratic displacement function and 16 degrees of freedom. The contrast of simulating result with the experimental result was shown in Fig. 6.

We can know from the above calculating results that the maximum relative error was less than 0·25%, which shows that the accuracy of calculating results coincides with the requirements and ANSYS is proved to be used for accurately calculate the creep of Babbitt.



6 Contrast of test curve with FEM creep curve



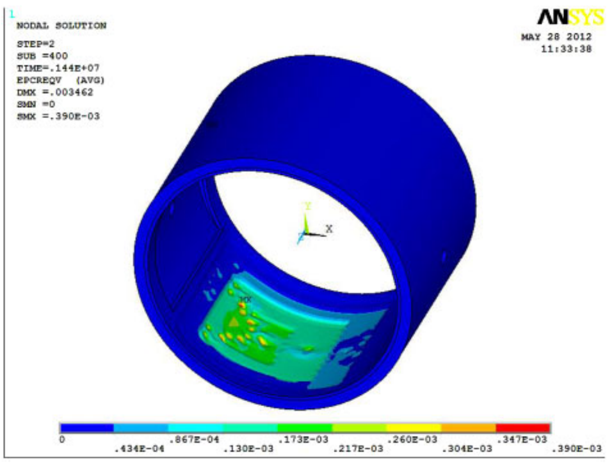
7 Mesh generation

According to the above analysis, to further grasp the creep properties of Babbitt of oil film bearing, on the basis of creep coefficient C_i (i=1–8) of Babbitt from creep test, FEM numerical simulation was done by ANSYS. SOLID186 with quadratic displacement function and strong solving ability was selected as finite element model unit of oil-film bearing model. The mesh generation of oil film bearing model was shown in Fig. 7. Two load steps were set up to analyse Babbitt creep. The first load step was set for initial calculation. During this process, creep solution command was closed, and the time step size was set as 1e-6*h*. The second load step was set for creep analysis. During this process, the creep solution command was opened, the time step was set as 800, and the solution time was set as 400 h.

The simulation results at 65°C −15 MPa show that the max creep deformation in the loading zone of bearing was 0·103 mm in 100 h, the max creep deformation was 0·142 mm in 300 h, and the max creep deformation was 0·154 mm in 400 h. The simulation results are shown in Fig. 8.

The creep features of oil film bearing Babbitt can be summarised as below:

(i) the creep strain mainly concentrated on the central zone with a larger load, the value was larger on the section with the largest load, i.e.



8 Creep strain nephogram of Babbitt at 65°C −10 MPa for 400 h

the zone corresponding with the minimum oil film thickness. However, the creep effect was not obvious in the marginal zones of loading area and non-loading zones

(ii) comparing with the creep strain at different time, the variation rate of creep strain in the majority zones was faster in the front 50 h, and tended to be stable after 50 h.

(iii) the creep strain continuously increases with time, and the zone with obvious creep deformation will externally expand. The expanding zone of Babbitt of oil film bearing mainly lies in the inlet side of dynamic lubricating oil

(iv) the simulation results show that creep phenomenon has been existing in Babbitt under the working surroundings; the creep magnitude belongs to micrometer level. Compared with the thickness of oil film, the creep belongs to the same magnitude and the higher. (The magnitude of oil film thickness is micrometre or nanometre.)

Conclusions

1. The creep test on Babbitt was done according to National Standards (GB/T2039-1997). The creep value of SnSb8Cu4 and SnSb11Cu6 can respectively reach 0·067 and 0·137 mm within 280 h at 65°C−15 MPa, which proves that the creep of Babbitt has obvious negative effect on the lubricating properties of oil film.

2. The stress relative exponents of the Graham creep model were calculated based on creep test data (as shown in Table 4). The Babbitt creep curves under any stress can be extrapolated.

3. The test specimen of SnSb11Cu6 was numerically simulated. The relative error of the calculated value and the experimental value is only 0·07% under the creep steady state. The feasibility and accuracy of using ANSYS to calculate Babbitt creep was verified, and the 3D entity of oil film bearing was numerically simulated by ANSYS. The results show that the largest creep strain was located in the zone with a larger load (the zone corresponding with the minimum oil film thickness), and the largest creep deformation was 0·154 mm in 400 h.

4. From the creep curves of both Babbitt, it can be known that the strain hardening is the major cause of Babbitt creep. The process of Babbitt creep can be considered as a competitive process of the alloy reversion and the dislocation multiplication by the strain hardening. The α solid solution of SnSb11Cu6 is more than that of SnSb8Cu4 and has some SnSb, which results in more probability of creep diffusion and creep dislocation of SnSb11Cu6. Therefore, the creep properties of SnSb11Cu6 will be relatively more obvious than that of SnSb8Cu4.

Acknowledgements

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