B. Z. WANG, X. M. HUANG, C. WANG, Z. Y. WANG, C. XING, H. C. JI

ISSN 0543-5846
METABK 58(3-4) 267-271 (2018)
UDC – UDK 669.715:539.374.001.41:620.173-536.45:620.16:512.3=111

CONSTITUTIVE EQUATIONS OF AA6111 ALUMINUM ALLOY

Received – Primljeno: 2019-01-01
Accepted – Prihvaćeno: 2019-03-20
Original Scientific Paper – Izvorni znanstveni rad

The hot compression test was conducted in Gleeble-1 500D to study the hot flow stress behavior of AA6 111 aluminum alloy belonging to Al-Mg-Si series, at the deformation temperatures ranging from 350 to 500 °C and strain rates ranging from 0,01 s^{-1} to 1 s^{-1}. And how the flow stress change with variation of strain, temperature and strain rate was investigated. The results show that flow stress increases with decreasing temperature and increasing strain rate; the AA6 111 is positive stain rate sensitive material; the main softening mechanism is dynamic recovery. Furthermore, constitutive equation considering the effect of strain was obtained based on Arrhenius equation. The predicted flow stress values well agree with the experimental results with some little aberration. The coefficient of association can be as high as 0,9 954, which shows high reference value for industry and simulation analysis.

Key words: AA6 111, investigation of plastic deformation, hot compression, flow stress, constitutive equation

INTRODUCTION

Vehicle lightweight is the mainstream of manufacturing design nowadays, the adoption of aluminum alloy instead of steel is one of the important ways of lightweight. Aluminum alloy has low density, high specific strength, specific modulus, fracture toughness, oxidation resistance, and good process forming performance, so it has been paid more attention and applied in aviation aerospace, automobile and other industries and scientific research fields [1-3]. AA6 111 aluminum alloy is a series of Al-Mg-Si alloy, Mg_2Si strengthening phase can be formed after certain heat treatment, so as to improve the strength of the material, and has good formability. At present, it is mainly used in the manufacturing of automobile parts, which is regarded as a promising material in the automobile industry and the preferred body material for many automobile manufacturing [4-6]. In the body manufacturing, the 6XXX series is mainly used in the production of automobile exterior plate, and can also be used in the production of automobile interior plate. Among them, Europe uses more AA6 016 aluminum alloy, and the United States uses more AA6 111 aluminum alloy [7]. With the development of automobile and the of lightweight process, aluminum alloy will be more applied in automobile and other industries, and the research on AA6 111 is of great significance.

B. Z. Wang, X. M. Huang, C. Wang, Z. Y. Wang, C. Xing, College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China; H. C. Ji (E-mail: jihongchao@ncst.edu.cn), College of Mechanical Engineering, North China University of Science and Technology, Hebei, Tangshan, China; National Center for Materials Service Safety, University of Science and Technology Beijing, China; School of Mechanical Engineering, University of Science and Technology Beijing, Beijing, China.

In this paper, the hot compression test was conducted by Gleeble-1 500D to obtain the stress-strain relationship curves at different temperatures and strain rates, to establish the flow stress constitutive equation on AA6 111 based on Arrhenius. The predicted value is in good agreement with the experimental value by the equation. The correlation coefficient can reach 0,9 954.

EXPERIMENTAL PROGRAM

The experimental material is AA6 111-T4 high-strength aluminum alloy of American aluminum corporation. First the aluminum alloy rod processed into 815 mm hot compression test specimen. Then the isothermal hot compression test was conducted in Gleeble-1500D, the deformation temperature is 350 - 500 °C, the strain rate is within the range of 0,01 - 1 s^{-1}. When doing the experiment, with 10 °C/s first heated to solid solution temperature is 550 °C, solid solution time 5 min. And fell to deformation temperature at 5 °C/s, compression is carried out after the heat preservation 60 s. Experiment data points are automatically collected by the equipment. Extract experiment data points, sort data, and processed experiment errors.

RESULTS AND ANALYSIS

Figure 1((a), (b), (c)) is the stress-strain curve of AA6 111 aluminum alloy at different temperature and strain rate. It can be seen from the Figure 1, the flow stress increases rapidly with the increase of strain. Because in the initial deformation stage, with the continuous increase of dislocation density, the hardening mechanism dominates, but the softening mechanism is not obvious. When the deformation reaches a certain stage, the softening mechanism of the material will gradually play a greater role due

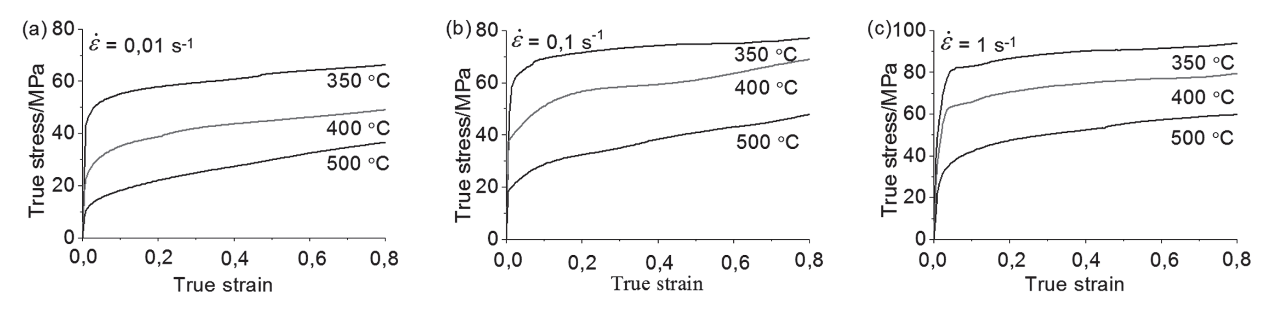

Figure 1 True stress-strain curves of AA6 111 aluminum alloy

to the recovery and recrystallization, so the flow stress increases slowly. The softening and hardening mechanisms compete with each other and gradually approach equilibrium, so the flow stress presents a relatively stable change trend within a certain strain range. Under the same strain rate, the flow stress along with the rise of temperature to drop, mainly because the temperatures make atomic energy of thermal motion increase and the bonding force between atoms reduce to reduce the material tensile ability. At the same time, the rise of temperature also contributed to the recovery and recrystallization softening mechanism, so as to make the flow stress rising trend. Under the same temperature, the flow stress increases with the increase of strain rate, the main cause of this phenomenon is the occurrence of the dislocation promoted under great strain rate, the unit time to participate in the increase in the number of dislocation motion, thus increase the degree of strain hardening alloy, used to happen at the same time fully softened time is shortened, lead to the increase of the flow stress. Thus, the strain rate sensitive coefficient of material is positive, AA6 111 is positive strain rate sensitive material. If the influence of temperature and strain rate on flow stress is further quantified, the temperature sensitivity coefficient and strain rate sensitivity coefficient under different deformation temperature and strain rate can be obtained according to the empirical formula and experimental data. When the stress passes through the yield point, the curve does not show an obvious downward trend, but a certain upward trend. The higher the temperature is, the more obvious it is. It shows that dynamic recrystallization is not significant and the softening mechanism is mainly dynamic recovery.

ESTABLISHMENT OF CONSTITUTIVE EQUATION

Constitutive equation is often used to estimate the flow stress of a material during thermal deformation. The material constants in the constitutive equation can be determined by the stress-strain data of the thermal compression test at different temperatures and rates. Under the condition of high-temperature deformation, the relationship between flow stress, temperature and strain rate can be expressed by Arrhenius equation. Moreover, the influence of temperature and strain rate on material deformation can be expressed by Zener-Holloman parameter(Z). Its expression is shown in equation (1) and (2):

$$Z = \dot{\varepsilon} exp\left(\frac{Q}{RT}\right) \quad (1)$$

$$\dot{\varepsilon} = Af(\sigma) exp\left(-\frac{Q}{RT}\right) \quad (2)$$

In the equation: $f(\sigma)$ is a stress function and has the following three forms:

$$f(\sigma) = \sigma^{n_1} \ (\alpha\sigma < 0,8) \quad (3)$$

$$f(\sigma) = \exp(\beta\sigma) \ (\alpha\sigma > 1,2) \quad (4)$$

$$f(\sigma) = [\sinh(\alpha\sigma)]^n \ (Full\, stress) \quad (5)$$

In the equation: σ – flow stress/MPa; T – temperature/K; R – gas content/8,3 144 $Jmol^{-1} \cdot K^{-1}$, Q – thermal deformation activation energy/$Jmol^{-1}$; A, n_1, n, β, α ($\alpha = \beta/n_1$) – material constant.

Normally, the power function is applied to the low stress region and the exponential function is applied to the high stress region. The hyperbolic sinusoidal stress gives a good linear relationship in different stress levels at different stress levels. However, these equations have some deficiencies in the description of the flow stress, because the influence of the strain on the flow stress is not considered in the equation.

DETERMINATION OF MATERIAL CONSTANT

In this paper, the influence of the strain variable on the material parameters of the equation is considered. The process of determining the material constant is introduced by taking the strain variable of 0,55 as an example.

The equation (6) and (7) can be obtained by combining with equation (2), (3) and (4).

$$\dot{\varepsilon} = B_1 \sigma^{n_1} \ (\alpha\sigma < 0,8) \quad (6)$$

$$\dot{\varepsilon} = B_2 \exp(\beta\sigma)(\alpha\sigma > 1,2) \quad (7)$$

B_1 and B_2 are material constants independent of deformation temperature. Take the logarithm of both sides of equation (6) and (7) can be obtained

$$ln\sigma = \frac{1}{n_1} ln\dot{\varepsilon} - \frac{1}{n_1} lnB_1 \quad (8)$$

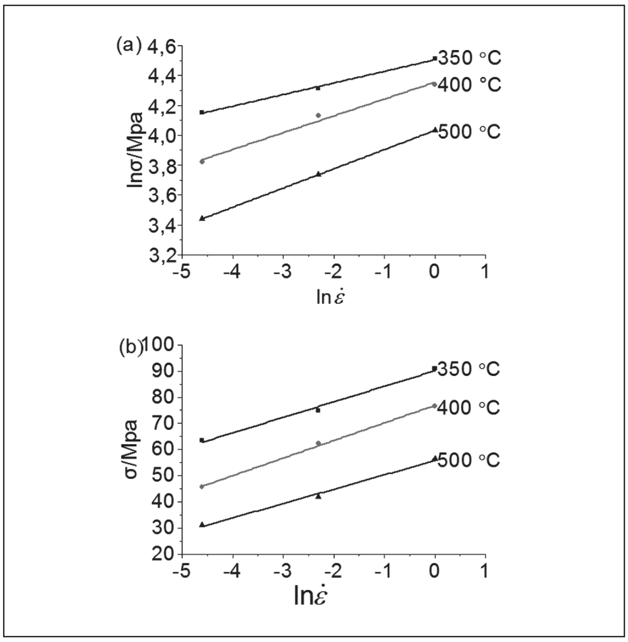

Figure 2 Relationship between true stress and strain rate

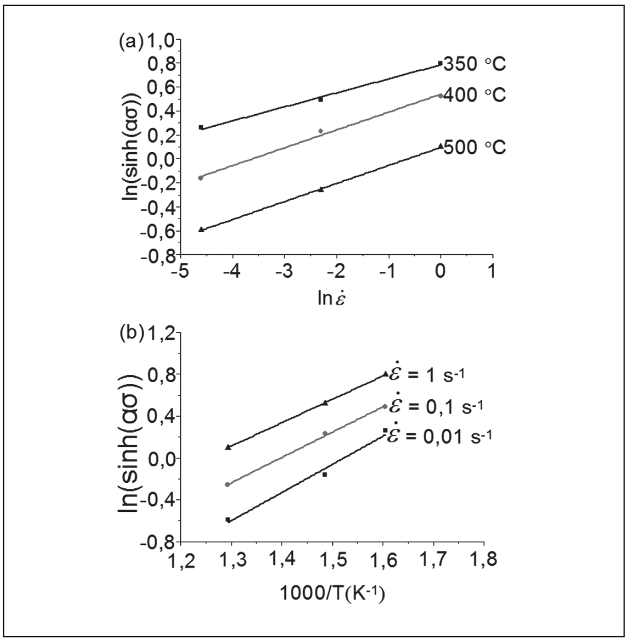

Figure 3 Relationship ln[sinh($\alpha\sigma$)] and strain rate, temperature

$$\sigma = \frac{1}{\beta} ln\dot{\varepsilon} - \frac{1}{\beta} lnB_2 \tag{9}$$

When strain variable is 0,55, plug different strain rate values and corresponding flow stress values into equation (8) and (9) to obtain the relationship between flow stress and strain rate, as shown in Figure 2. It can be seen that the flow stress in the hot compression deformation of aluminum alloy can be predicted by such a group of parallel lines. Due to each hot compression experiment is carried out at the same temperature, partial differential of equation (8) and (9) can obtain equation (10) and (11):

$$n_1 = [\frac{\partial ln\dot{\varepsilon}}{\partial ln\sigma}]_T \tag{10}$$

$$\beta = [\frac{\partial ln\dot{\varepsilon}}{\partial \sigma}]_T \tag{11}$$

By calculating the slope of the line in the figure, can obtain the n_1 and β values at different deformation temperatures. The average values of n_1 and β are 9,851 and 0,167, respectively. Further, obtain $\alpha = \beta/n_1 = 0{,}017$.

For the whole flow stress state including high stress zone and low stress zone, a hyperbolic sinusoidal model can be used to describe.

$$\dot{\varepsilon} = A\left[\sinh\left(\alpha\sigma\right)\right]^n exp\left(-\frac{Q}{RT}\right) \tag{12}$$

Take the logarithm of both sides of the equation can get:

$$\ln\left[\sinh\left(\alpha\sigma\right)\right] = \frac{ln\dot{\varepsilon}}{n} + \frac{Q}{nRT} - \frac{lnA}{n} \tag{13}$$

Partial differential of equation (13) to get:

$$n = \left\{\frac{\partial ln\dot{\varepsilon}}{\partial \ln\left[\sinh\left(\alpha\sigma\right)\right]}\right\}_T \tag{14}$$

$$Q = nR\left\{\frac{\partial \ln\left[\sinh\left(\alpha\sigma\right)\right]}{\partial(1/T)}\right\}_{\dot{\varepsilon}} \tag{15}$$

In order to obtain the n value, the relation diagram of ln[sinh($\alpha\sigma$)] – $\ln\dot{\varepsilon}$ under different deformation temperatures can be drawn when the strain is 0,55, as shown in Figure 3 (a). The slope of the regression line obtained is the reciprocal of the material constant n. The average value of n obtained at different temperatures is 7,300. In the same way, draw the relation diagram of ln[sinh($\alpha\sigma$)] – 1000/T under different deformation rates, as shown in Figure3 (b). Plug the slope of the regression line under different deformation rates and the corresponding n and R values into equation (15) can obtain the Q values under different strain rates, and then take the average value of 148,616KJ/mol.

In the end compute the value of A. According to equation (13), you can obtain $\ln A = Q/(RT) - nH$, and H is the intercept value of the linear fitting of ln[sinh($\alpha\sigma$)] – $\ln\dot{\varepsilon}$. lnA = 22,464 are obtained.

THE STRAIN COUPLING OF CONSTITUTIVE EQUATION

Because the equation (2) does not involve strain variable. In many related public literatures, the influence of strain change on flow stress is seldom mentioned. However, it can be seen from Figure 1, the effect of strain is very obvious, especially in the initial stage of compression. At the same time, it can be seen from Figure 4 ((a), (b), (c), (d)) that the material constant is significantly affected by strain. Therefore, it is necessary to consider the effect of strain into the equation, and the stress value can be predicted better. Calculate the values of material constants (α, n, Q, A) at different strains, 7 strain values were taken between 0,15 and 0,75 with an interval of 0,1, and then the obtained data were fitted. Generally, the number of fitting polynomials is between 4 and 6. After continually attempt, it is found that the fitting effect is better by using the quintic polynomial to

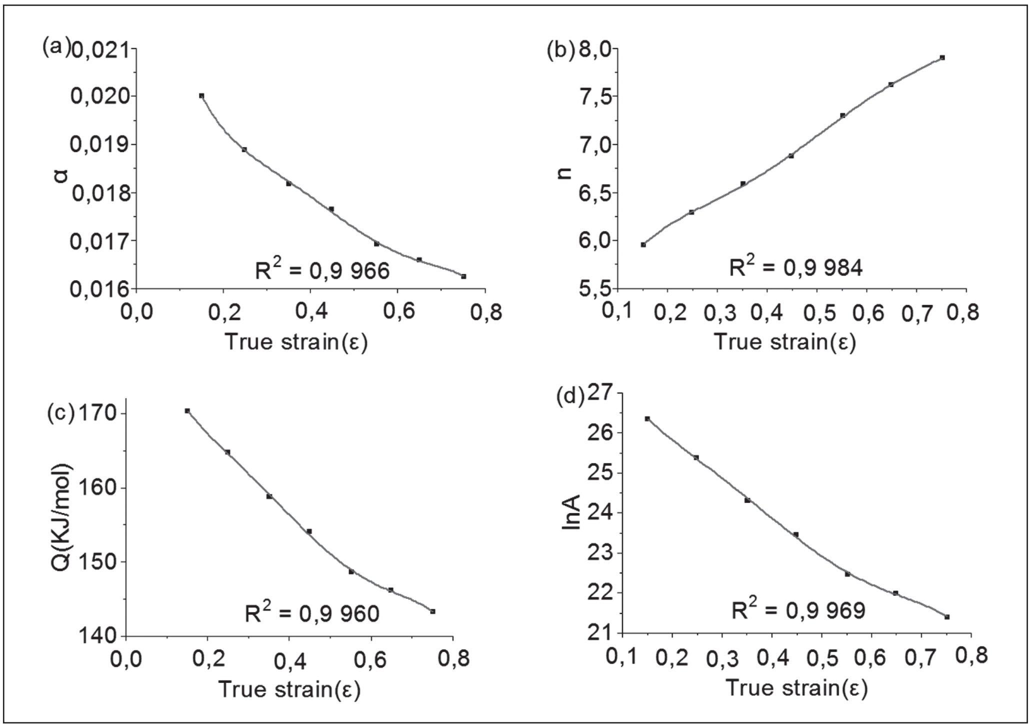

Figure 4 5th order polynomial fit between model parameters and strain

fit the relationship between them. The correlation coefficient can reach above 0,9 960.

The fitting polynomials of each parameter are as follows:

$$\alpha = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5$$
$$n = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5$$
$$Q = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5$$
$$lnA = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5$$

The fitting polynomial coefficients are shown in Table 1.

Table 1 **Coefficients of polynomial for material parameters**

α	n			Q		lnA	
B_0	0,027	C_0	4,252	D_0	190,894	E_0	29,814
B_1	-0,081	C_1	20,817	D_1	-242,004	E_1	-40,926
B_2	0,352	C_2	-89,925	D_2	1 051,98	E_2	179,229
B_3	-0,801	C_3	206,488	D_3	-2 784,4	E_3	-481,761
B_4	0,874	C_4	-216,718	D_4	3 449,83	E_4	602,610
B_5	-0,363	C_5	84,578	D_5	-1 578,6	E_5	-277,889

When the material constant is determined, the expression of the flow stress containing the Z parameter can be written according to equation (1) and (12):

$$\sigma = \frac{1}{0,017} ln\left\{\left(\frac{Z}{5,7\times10^9}\right)^{1/7,300} + \left[\left(\frac{Z}{5,7\times10^9}\right)^{2/7,300} + 1\right]^{1/2}\right\}$$

VERIFICATION OF CONSTITUTIVE EQUATION

In order to verify the accuracy of the established constitutive equation, the predicted values were calcu-

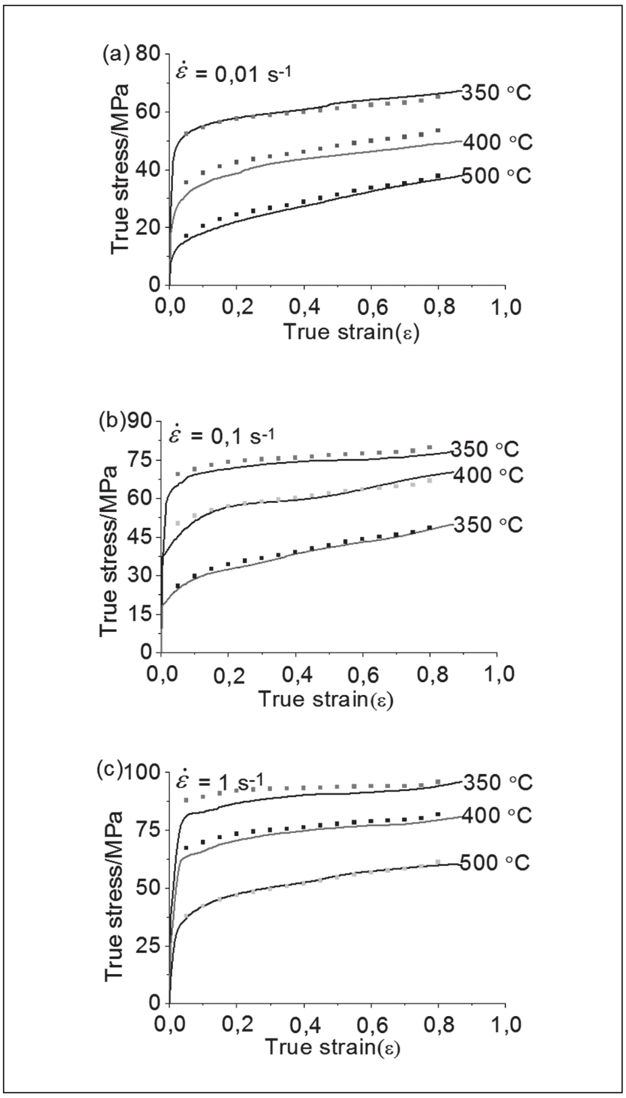

Figure 5 Comparison between experimental and predicted results

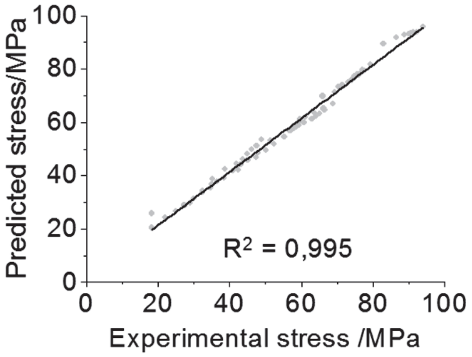

Figure 6 Correlation between experimental and predicted values

lated by the constitutive equation is compared with the experimental value, as shown in Figure 5 ((a), (b), (c)).

Generally speaking, the prediction of flow stress by constitutive equation is relatively accurate, and the correlation coefficient between the experimental and the predicted value of flow stress is more than 0,995, as shown in Figure 6. Therefore, the equation has high applicability.

CONCLUSION

(1) Flow stress of AA6 111 aluminum alloy decreased with the increase of temperature under the same strain rate in the process of hot compression deformation. At the same temperature, the flow stress increases with the increase of strain rate. It is a normal strain rate sensitive material. The relationship among flow stress, strain rate and temperature can be expressed by Arrhenius equation with Zener-Holloman parameters.

(2) The constitutive equation of AA6 111 aluminum alloy was established, and considered the effect of strain variable on flow stress. It can predict flow stress accurately. Scope of application, the strain between 0,05 - 0,8, strain rate between 0,01 - 0,1s^{-1}, the temperature is between 350 - 500 °C.

(3) By comparing with the experimental value, the correlation coefficient between the predicted value and the experimental value of the established constitutive relation in this paper is above 0,995. It is shown that the constitutive relationship of AA6 111 aluminum alloy can accurately predict the flow stress in the experimental range.

Acknowledgments

This research was funded by China Postdoctoral Science Foundation (NO. 2018M641186).

REFERENCES

[1] W S Miller. Recent development in Aluminum alloys for the automotive industry. Materials Science & Engineering A 280(2000), 37-49.

[2] Huang X, Zhang H, Han Y I, et al. Hot deformation behavior of 2026 aluminum alloy during compression at elevated temperature. Materials Science & Engineering A 527(2010), 485-490.

[3] Dong X, Yang H, Zhu X, et al. High strength and ductility aluminum alloy processed by high pressure die casting. Journal of Alloys and Compounds 773(2019),86-96.

[4] Mcmurray H N, Holder A, Williams G, et al. The kinetics and mechanisms of filiform corrosion on aluminum alloy AA6111. Electrochimica Acta 55(2010),7843-7852.

[5] Khatwa M K A, Malakhov D V. On the thermodynamic stability of intermetallic phases in the AA6111 aluminum alloy. CALPHAD: Computer Coupling of Phase Diagrams and Thermochemistry 30(2006), 0-170.

[6] Zhou X, Liu Y, Thompson G E, et al. Precipitation in an AA6111 Aluminum Alloy and Cosmetic Corrosion. Acta Materialia 55(2007), 353-360.

[7] Baczynski G J, Guzzo R, Ball M D, et al. Development of roping in an aluminum automotive alloy AA6111. Acta Materialia 48(2000), 3361-3376.

Note: The responsible translator for English language is Y M Li-North China University of Science and Technology, China