Prediction Model of Microstructure and Properties of Al Foil Alloy During Thermal Deformation

Wenduan Yan¹, Yan Li¹,⁎, Yanhua Xu¹,⁎, Wanqing Lai² and Xiumin Zhou¹

¹Minnan University of Science and Technology, Shishi, Quanzhou, 362700, China
²Quanzhou Arts and Crafts Vocational College, Dehua, Quanzhou, 362500, China
⁎Corresponding author: emily007@126.com (Yan Li); 290818687@qq.com (Yanhua Xu)

Abstract. Prediction model of microstructure and properties of Al foil alloy was established by thermo-simulation compression experiment. The relationships between grain size, material constants, and flow stress were studied. In thermal deformed Al foil alloy, the relationship between grain size and material parameter Z met an approximately linear relationship, and an unitary linear regression equation was established. The influence of grain size on flow stress during thermal deformation was highly significant. The prediction models could thus predict the structure of the alloy during thermal deformation effectively, and guide the Al foil rolling.

1. Introduction
Aluminum foil is a kind of flexible metal which is made by repeatedly rolling commercial pure aluminum. Aluminum foil stock is mainly used for containers, building insulation, capacitor, and cooking bags, and all of them have the advantages of innocuity, health, flexibility, etc [1-3]. A typical aluminum foil alloy is 1235 Al alloy. Hot rolling is one of the key processes affecting the final properties of aluminum sheet. The rolling temperature, rolling rate, interpass residence time, and genetic properties of interpass microstructure have a great influence on the performance through the whole hot rolling and the subsequent processing [4-7]. By quantitative study, modeling of the grain structure, flow stress, and material constant (parameter Z) of aluminum foil alloy is beneficial to the prediction and control of microstructure and properties of the alloy during hot rolling, and guide the deformation processing of the Al stock.

2. Experimental
As an aluminum foil alloy, 1235 Al alloy was chosen as the experimental material. The chemical composition of the 1235 Al alloy was shown in Table 1. Melt treatment of conventional refining was used in the alloy during melting, and the impurity content was 0.154 %. Ingots were dealt with homogenizing annealing by condition of annealing temperature of 833 K, holding for 13 h, air-cooled [8]. The size of specimen used for compression was 10 mm in diameter and 12 mm in height. Isothermal axisymmetric compression tests were held in Geeble-1500 dynamic thermal / mechanical simulation machine with conditions of deformation temperature of 573 K, 623 K, 673 K, 723 K, and 773 K, strain rate of 0.01 s⁻¹, 0.1 s⁻¹, 1 s⁻¹, 10 s⁻¹, and 50 s⁻¹, compression deformation of 50 % [9-11].

In thermal deformation experiment, the system did the real-time collection of temperature, displacement, true stress, true strain and other parameters. Water quenching was used immediately at...
the end of thermal compressing with the delay time of less than 0.1 s to keep the deformation structure unchanged.

Table 1. Chemical composition of Al foil alloy (1235 Al alloy).

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Ni  | Zn  | Ti  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| wt.%    | 0.095 | 0.38 | 0.002 | 0.002 | 0.0001 | 0.0001 | 0.006 | 0.015 | Remains |

Samples after thermal compression were cut into longitudinal sections with direction paralleling to the compression by WEDM of DK7255, and were processed into thin slices. Metallographic samples were prepared, and microstructure was observed by horizontal metallographic polarizing microscope of XJG-05. The average grain size d was measured by the metallographic analysis system TCI shown in Table 2.

3. Results

3.1. Stress and strain curves

The flow stress curves of 1235 Al alloy during hot deformation are shown in Figure 1. The peak flow stress and steady flow stress are shown in Table 2 corresponding to the Figure 1. Grain size d in the table is measured by the metallographic analysis system.

![Flow stress curves](image)

Fig. 1. Flow stress curves of 1235 Al alloy during hot deformation with a) different deformation temperature at strain rate of 0.1 s⁻¹, b) different strain rates at deformation temperature of 673 K, c) different deformation temperature at strain rate of 1 s⁻¹, and d) different deformation temperature at strain rate of 50 s⁻¹.

From Figure 1, 1235 Al alloy shows obvious work hardening and steady flow characteristics. The flow stress under thermal compression varies with changing deformation temperature and strain rate.
At different deformation conditions, the flow stress first increases rapidly, then decreases and comes steady-state. The steady state flow stress shrinks with the increasing deformation temperature, however, it enlarges with the increasing strain rate.

Table 2. Peak stress, flow stress and the average grain size of 1235 Al alloy during hot deformation.

| T/K   | \(\dot{\varepsilon}\), \(\text{hr}^{-1}\) | \(\sigma_p/\text{MPa}\) | \(\sigma_s/\text{MPa}\) | \(d/\mu\text{m}\) |
|-------|----------------------------------------|-----------------|-----------------|----------------|
| 673   | 0.01                                   | 23.64           | 17.03           | 85.1           |
| 673   | 0.1                                    | 34.65           | 28.51           | 78.6           |
| 673   | 1.0                                    | 38.33           | 38.25           | 75.8           |
| 673   | 10.0                                   | 63.32           | 47.37           | 71.0           |
| 673   | 50.0                                   | 85.56           | 60.30           | 66.2           |
| 573   | 0.1                                    | 50.31           | 49.21           | 69.8           |
| 623   | 0.1                                    | 41.32           | 37.63           | 73.5           |
| 723   | 0.1                                    | 28.71           | 20.66           | 89.7           |
| 773   | 0.1                                    | 23.15           | 13.15           | 101.4          |
| 573   | 1.0                                    | 65.30           | 61.94           | 70.4           |
| 623   | 1.0                                    | 56.46           | 49.22           | 70.5           |
| 723   | 1.0                                    | 32.62           | 24.86           | 88.1           |
| 773   | 1.0                                    | 27.13           | 16.82           | 90.2           |
| 573   | 50.0                                   | 88.69           | 71.21           | 66.4           |

From Figure 1 and Table 2, at a certain strain rate, the higher the deformation temperature is, the lower the peak stress and steady flow stress are, and the more obvious the dynamic softening occurs. At a certain deformation temperature, the higher the strain rate is, the higher the peak stress and steady-state flow stress are, and the tendency of work hardening is increased.

3.2. Material constants

Multiple linear regression is an effective way to calculate the material constants of aluminum alloys. In regression, there is an instability in calculation because of small data capacity of peak stress. On the contrary, the steady flow stress regression is adopted to reduce the solving error with large data capacity and good stability. Material constants calculated by steady flow stress regression are more reliable. Therefore, multiple linear regression of steady state flow stress could be used to obtain the multiple linear relationship among strain rate, deformation temperature, and flow stress, shown in equation (1) [12-14].

\[
\ln \dot{\varepsilon} = \ln A - \frac{Q}{RT} + n \ln [\sinh(\alpha \sigma)]
\]  

(1)

\[
\ln \dot{\varepsilon} = D_1 + \frac{D_2}{T} + D_3 \ln [\sinh(\alpha \sigma)]
\]  

(2)

Constant D_1, D_2, and D_3 in equation (2) were regression parameters.

The steady flow stress and corresponding strain rate and deformation temperature collected by real-time in 1235 Al alloy during thermal deformation are substituted into equation (2) for multiple linear regression to solve the material constant of the alloy.

Table 3 showed the regression results of flow stress and thermal deformation conditions, and the material constants of 1235 Al alloy obtained by multiple linear regressive analysis are shown in Table 4.
Table 3. Regression analysis results of flow stress and thermal deformation conditions.

| Regression analysis results | Multiple correlation coefficient R | F-test | Statistical significance |
|-----------------------------|------------------------------------|--------|-------------------------|
| $\ln \dot{\varepsilon} = 25.97 - 20691.78/T + 5.40 \ln \sinh(0.0326\sigma_s)$ | 0.9542 | 2054 | 4.61 | ** |

Table 4. Material constants of 1235 Al alloy obtained by multiple linear regressive analysis.

| A(S^{-1}) | Q(kJ/mol) | $\alpha$(mm²/N ) | n | m |
|-----------|-----------|------------------|---|---|
| $1.8994 \times 10^{11}$ | 172.03 | 0.0326 | 5.40 | 0.1343 |

From Table 4, A is the structure factor, N is the stress index, M is the strain rate sensitivity coefficient, and Q is the thermal deformation activation energy.

3.3. Prediction model

In order to comprehensively consider the influence of the main thermal deformation conditions on the flow stress under a certain thermal deformation, the relationship between the deformation conditions and the high temperature flow stress can be studied by parameter of Zener-Hollomon, seen in equation (3) [15-17].

$$Z = A[\sinh(\alpha\sigma_s)]^n = \dot{\varepsilon} \exp(Q/RT)$$ (3)

Parameter Z of 1235 aluminum alloy under different deformation conditions could be obtained according to the thermal deformation activation energy obtained by multiple linear regression.

Take the natural log of both sides of equation (3), and the result is shown in equation (4).

$$\ln Z = \ln A + n \ln[\sinh(\alpha\sigma)]$$ (4)

At a certain deflection, the grain morphology of 1235 Al alloy mainly depended on the deformation temperature and strain rate (i.e., parameter Z). Therefore, it is beneficial to predict and control the microstructure and properties of deformed aluminum foil alloy by discussing the internal relationship among grain structure, properties (flow stress), and deformation parameter (parameter Z) quantitatively.

In general, the relationship between the average grain size and the parameter Z of Zener-Hollomon could meet the formula of Hall-Petch, shown in equation (5).

$$d^{-1} = a + b \ln Z$$ (5)

Equation (3) is substituted into the equation (5), and the result is shown in equation (6).

$$d^{-1} = a' + b' \ln[\sinh(\alpha\sigma)]$$ (6)

According to the relation of parameter Z, parameter Z and its natural logarithm $\ln Z$ are calculated from the thermal deformation material constant. Table 5 shows the Z values and the corresponding calculation results of aluminum foil alloy at different deformation conditions.

The values of $d^{-1}$ and $\ln Z$ or $\ln[\sinh(\alpha\sigma_s)]$ in Table 5 are used in equation (5) or equation (6) respectively for linear regression analysis, and the results are shown in Table 6.

Table 5. Z values and the corresponding calculation results of 1235 Al alloy at different deformation conditions.

| T/K | $\dot{\varepsilon}$ $s^{-1}$ | Q(kJ/mol) | $\alpha$ | $\sigma_s$MPa | d/μm | $d^{-1}$ | lnZ | ln[$\sinh(\alpha\sigma_s)$] |
|-----|----------------|----------|---|------------|-----|--------|------|-------------------|
| 673 | 0.01 | 171.32 | 0.0334 | 17.03 | 85.1 | 0.0118 | 26.03 | -0.511 |
Table 6. Regression analysis results of grain size and parameter Z, or stress state in deformed 1235 Al foil alloy.

| $d_{-1}$ | Correlation r | $r_{0.001(n-2)}$ | Significance |
|----------|---------------|------------------|--------------|
| $d_{-1}=0.0023+3.54 \times 10^{-4}\ln Z$ | 0.9278 | $r_{0.001(14-2)}=0.780$ | ** |
| $d_{-1}=0.0121+0.00202 \ln[\sinh(\alpha\sigma_s)]$ | 0.9598 | $r_{0.001(14-2)}=0.780$ | ** |

In Table 6, value $d$ is the grain size, $Z$ is the parameter Z, $\sigma_s$ is the steady flow stress, and $\alpha$ is the stress level parameter.

From above, the value of $d_{-1}$ and the value of $\ln Z$ of the deformed 1235 Al alloy satisfied a linear relationship, and the regression result is highly significant. The value of $d_{-1}$ and the value of $\ln[\sinh(\alpha\sigma_s)]$ of the alloy also satisfy the unary linear relationship, and the result is highly significant too. Therefore, the stable flow stress results and parameter $Z$ could be used to predict the hot deformation structure of the alloy during thermal deformation, and guide the foil rolling finally.

4. Conclusions

(1) The average grain size and the parameter $Z$ of Zener-Hollomon satisfy a highly significant linear relationship in 1235 Al alloy during hot deformation, and the model is $d_{-1}=0.0023+3.54 \times 10^{-4}\ln Z$.

(2) The average grain size and the parameter $Z$ of Zener-Hollomon satisfy a highly significant linear relationship. There is a highly significant linear relationship between the average grain size and steady flow stress in the alloy, and the model is $d_{-1}=0.0121+0.00202 \ln[\sinh(\alpha\sigma_s)]$.

(3) The prediction model could effectively predict the structure of the alloy during compression. It is helpful to guide rolling and improve the quality of aluminum foil products.

Acknowledgements

The authors acknowledge with gratitude the financial support received from the Science and Technology Program of Quanzhou (2019G037), Fujian Provincial Department of Education (JAT200769), China.

References

[1] A.A. Tiamiyu, A.Y. Badmos, A.G. Odeshi, J.A. Szpunar, Mater. Sci. Eng. A 10, 492-502 (2017)
[2] G.Y. Tan, Y.C. Yue, R.K. Cao, G. Yang, N. Ma, Heat Treat. Met., 7, 104-106 (2016)
[3] T. Dursun, C. Soutis, Mater. Design, 56, 862-871 (2014)
[4] W. Yan, G. Fu, H. Chen, L. Song, W. Liu, Mater. Tech. 53, 821-825 (2019)
[5] M. H?Rtel, B. Bohne, M. Wagner, Mater. Sci. Eng. 181, 12-14 (2017)
[6] W. Yan, G. Fu, Mater. Tech. 46, 637-642 (2012)
[7] H. Hallberg, A. Chamanfar, N. Nanninga, Appl. Math. Model. 81, 253-262 (2020)
[8] W. Yan, G. Fu, X. Zhou, D. Chen, Key Eng. Mater. 846, 77-81 (2020)
[9] K.T. Son, M.H. Kim, S.W. Kim, J. Alloys Compd. 740, 96-108 (2018)
[10] W. Yan, G. Fu, H. Chen, J. Mater. Eng. Perform. 21, 2203-2206 (2012)
[11] G. Kanel, A. Savinykh, G. Garkushin, S. Razorenov, J. Appl. Phys. 127, 035901 (2020).
[12] G. Maizza, R. Pero, M. Richetta, R. Montanari, J. Mater. Sci. 53, 1-11 (2020)
[13] S. Liu, S. Wang, L. Ye, Y. Deng, X. Zhang, Mater. Sci. Eng. A 677, 203-210 (2016)
[14] T. Zhang, S. Lu, J. Zhang, Z. Li, P. Chen, H. Gong, Y. Wu, Model. Simul. Mater. Sci. Eng. 25, 265-275 (2017)
[15] X. Liu, S. Han, L. Chen, S. Yang, M. Jin, B. Guo, T. Mao, Metall. Mater. Trans. A 48, 2336–2348 (2017)
[16] K. Sakino, J. Soc. Mater. Sci. Jap. 67, 964-969 (2018)
[17] S. Liu, Q. Pan, H. Li, Z. Huang, K. Li, X. He, X. Li, J. Mater. Sci. 54, 4366-4383 (2019)