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Deformation resistance of Fe–Mn–V–N alloy under different deformation processes

Yun-Li Feng*, **Jie Li**, **Li-Qun Ai**,
Bao-Mei Duan

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Abstract The deformation resistance of Fe–Mn–V–N alloy under different deformation conditions was investigated by hot compression method on thermal simulator. Effects of deformation degree, deformation temperature, and strain rate on deformation resistance were analyzed. The results show that when other conditions are constant, the deformation resistance increases with the increase in deformation degree and strain rate and decreases with the increase in deformation temperature. At the same time, the mathematical model of deformation resistance for Fe–Mn–V–N alloy was established by 1stOpt software using the Levenberg–Marquardt optimization algorithm carried out on the fitting of regression coefficients, which has higher fitting precision.

Keywords Fe–Mn–V–N alloy; Deformation process; Deformation resistance; Mathematical model

1 Introduction

Deformation resistance is an important factor to affect rolling force of metal during hot rolling. Deformation resistance values are essential in designing and checking pressure processing equipment, calculating force and power in all kinds of pressure processes, establishing mathematical model of the rolling force, and formulating process procedure and other aspects. At the same time, it can also reveal the changes of microstructure and mechanical properties of metals and alloys in the process of deformation, the mechanism of plastic deformation and its rule [1–5]. In order to improve the computer online control ability, product quality, and the stability of rolling process, the deformation resistance model of correctly reflected deformation process parameters was established, which has an important engineering value and academic significance.

In this work, the deformation resistances at different deformation temperatures, deformation degree, and strain rates were measured in the thermal simulation experiment. The mathematical model of deformation resistance for the Fe–Mn–V–N alloy was established through analyzing the factors of deformation resistance, providing a theoretical basis to determine exact mill load and formulate reasonable rolling technology.

2 Experimental

2.1 Materials

The experiment material was continuous casting billet of Fe–Mn–V–N alloy produced by some steelworks, and the chemical compositions (wt%) is C 0.16, Mn 1.40, Si 0.36, Al 0.022, V 0.057, N 0.0092, S 0.0090, P 0.020, and Fe bal.

2.2 Measurements

Thermal simulation experiments were performed on Gleeble-3500 thermal simulator. The size of specimens was Φ8 mm × 15 mm. Deformation scheme was as follows: the specimens were heated up to 1200 °C at a rate of

Y.-L. Feng*, J. Li, L.-Q. Ai, B.-M. Duan
College of Metallurgy and Energy, North China University of Science and Technology, Tangshan 063009, China
e-mail: tsfengyl@163.com

Y.-L. Feng, J. Li, L.-Q. Ai, B.-M. Duan
Key Laboratory of the Ministry of Education for Modern Metallurgy Technology, Tangshan 063009, China

10 °C·s^{-1} and held for 10 min and then cooled down to the deformation temperature at a rate of 10 °C·s^{-1}. Then, the specimens were deformed, respectively, at the temperatures of 1100, 1050, 1000, 950, 900, 850, 800 and 750 °C. The reduction rate was 60 %, and the strain rates were 0.1, 1.0, 10.0, and 30.0 s^{-1}. The specimens specimens were air-cooled after deformation. The microstructures of specimens were characterized by scanning electron microscopy (SEM, FEI QANT 650).

3 Analysis of experimental results

3.1 Analysis of true stress–strain curve

The curves of true stress–strain under different deformation conditions are shown in Fig. 1. It can be seen that the deformation resistance sharply increases with the increase in deformation degree, when it reaches a certain stress value, obvious peak value appears and then decreases to a relatively stable value both in the curves in Fig. 1a with the temperature from 950 to 1100 °C and in Fig. 1b at 1100 °C. However, peak value appears and then decreases without any obvious stable value in the curves in Fig. 1a at 900 °C, Fig. 1b at 1000 and 1050 °C, Fig. 1c at 750 °C, and Fig. 1d with temperature from 750 to 900 °C. Other curves have more stable stress value without a peak value. At the same time, it also can be seen that the higher the deformation temperature is, the lower the deformation resistance is in each figure when the strain rate conditions are the same.

3.2 Analysis of effects of deformation conditions on deformation resistance

The capacity of resisting deformation in unit cross-sectional area was called the metal plastic deformation resistance when plastic deformation was conducted under certain deformation conditions [1]. It is one of the most important parameters that calculate parameters of equipment capacity and make reasonable rolling process [6, 7]. Researches on deformation resistance show that the factors influencing deformation resistance include chemical composition and microstructure of the materials, deformation temperature, strain rate, deformation degree, stress state, and environmental media [1, 8]. Among them, the effects of deformation temperature, strain rate, and deformation degree on deformation resistance of metallic materials are the most obvious.

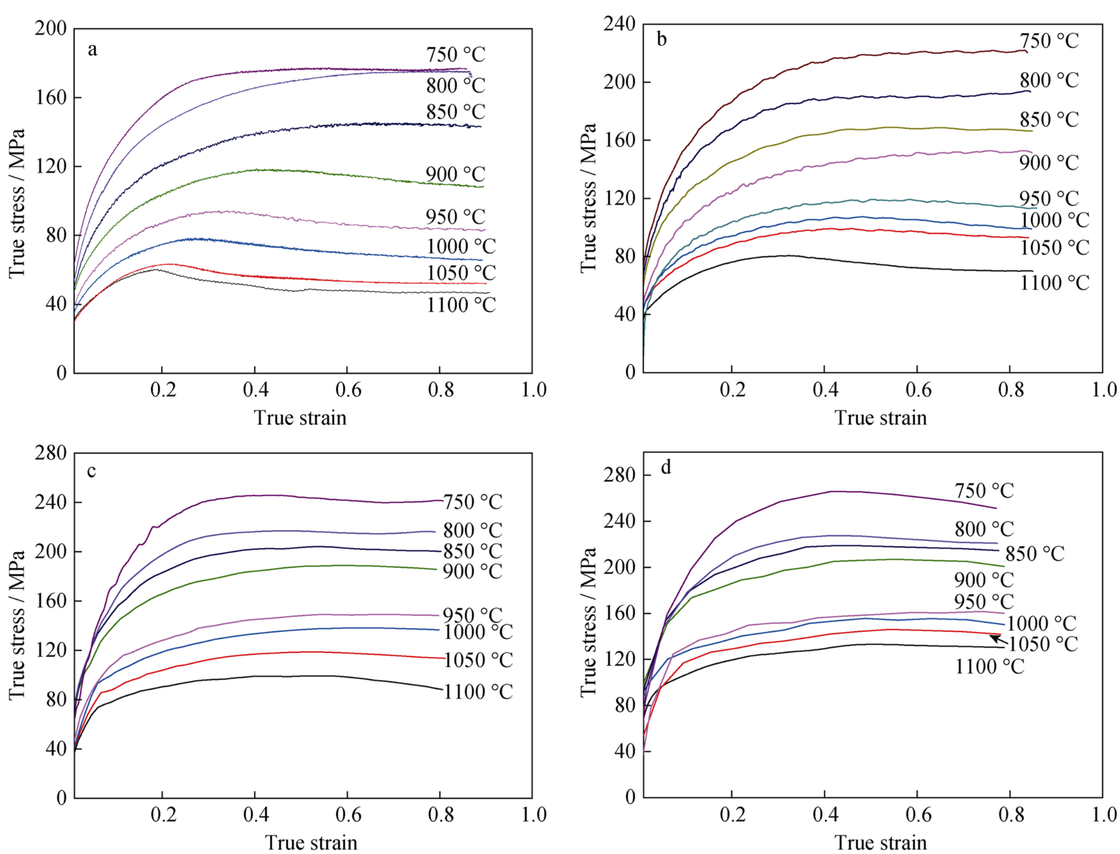

Fig. 1 Curves of true stress–strain at strain rates of **a** 0.1, **b** 1.0, **c** 10.0, and **d** 30.0 s^{-1}

3.2.1 Effect of deformation temperature on deformation resistance

The deformation temperature is the most significant factor affecting the deformation resistance. The effect of deformation temperature on deformation resistance under various strain rates was analyzed at deformation degree of 0.4. According to the curves of true stress–strain in Fig. 1, when the deformation degree is 0.4, the deformation resistance values under different deformation temperatures and various strain rates were calculated, as shown in Table 1. According to the data in Table 1, the curves of deformation temperature and deformation resistance were drawn, as shown in Fig. 2.

As seen from Fig. 2 and Table 1, deformation resistance decreases rapidly with the increase in deformation temperature. The reasons are as follows [9–15]. (1) The higher temperature is more conducive to the occurrence of dynamic recovery and dynamic recrystallization. Softening can be strengthened, and work hardening is abated or eliminated owing to the plastic deformation, and thus the deformation resistance decreases obviously. At the same time, the dynamic recovery caused by increasing temperature will reduce the number of point defects such as vacancy and interstitial atoms. The pinning effect of dislocation is weakened. The critical shear stress is required when the dislocation slip reduces and the dislocation movement is easier to make the deformation resistance decrease. (2) When the temperature increases, the atomic vibration is exacerbated, the kinetic energy of the atoms increases, and the binding force between atoms is weakened, which makes the atoms in an unstable state. The atoms are easy to be moved along the stress field gradient direction under the action of external force, so that plasticity increases and deformation resistance decreases. At the same time, new slip system may occur at high temperature, and rising temperature makes the slip resistance reduce. New slip systems and cross-slip are produced and started constantly, making deformation occur at lower stress, i.e. the deformation resistance reduces. (3) The addition of microalloying elements Nb, V, and Ti enhances the deformation resistance of austenite. The contribution of Nb and Ti is larger than that of V. This is attributed to the solid solution of the microalloying elements in the austenite. On the other hand, the Nb(C, N) and Ti(C, N) precipitated under the deformation temperature suppress the recrystallization of the austenite. However, in low carbon steel, the V(C, N) precipitates mostly in the temperature range of ferrite rather than that of austenite above 750 °C, which hardly influences the deformation resistance of austenite. The contribution of V to the deformation resistance is mostly caused by the V dissolved in austenite [9].

The microstructures of the specimens deformed, respectively, at the temperatures of 750, 950, and 1100 °C are shown in Fig. 3. The reduction rate is 60 %, and the strain rate is 1.0 s^{-1}. The specimens were air-cooled after deformation. It can be seen from Fig. 3 with the decrease in deformation temperature, the ferrite and pearlite obtained

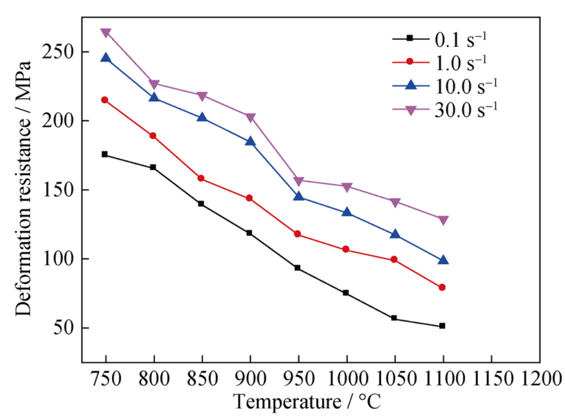

Fig. 2 Curves of deformation temperature versus deformation resistance with deformation degree of 0.4 at different strain rates

Table 1 Deformation resistance under different deformation temperatures (T) and various strain rates ($\dot{\varepsilon}$) with deformation degree of 0.4 (MPa)

T/°C	$\dot{\varepsilon}=0.1\ s^{-1}$	$\dot{\varepsilon}=1.0\ s^{-1}$	$\dot{\varepsilon}=10.0\ s^{-1}$	$\dot{\varepsilon}=30.0\ s^{-1}$
1100	50.787	78.449	98.525	128.831
1050	56.213	98.753	117.309	141.585
1000	74.459	106.202	133.238	152.596
950	92.590	117.157	144.809	156.858
900	118.066	143.191	184.631	203.033
850	138.951	157.472	201.913	218.484
800	165.459	188.292	216.339	227.008
750	174.869	214.292	245.268	264.481

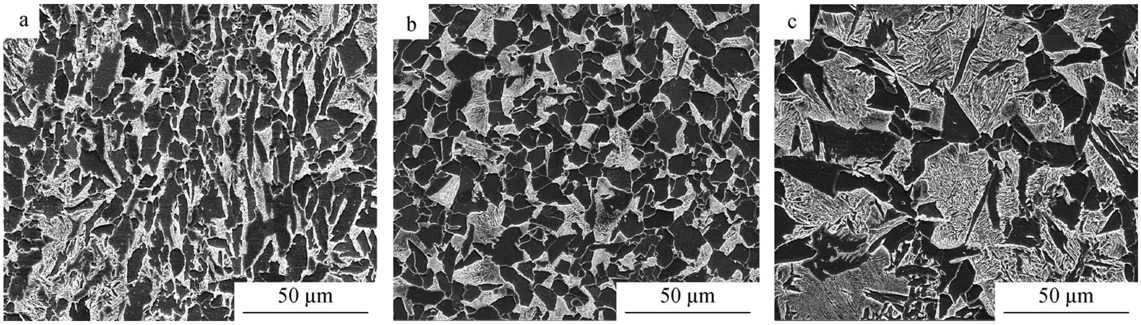

Fig. 3 SEM images of microstructure air-cooled to room temperature after deformation under different deformation temperatures at the strain rate of 1.0 s^{-1}: **a** 750, **b** 950, and **c** 1100 °C

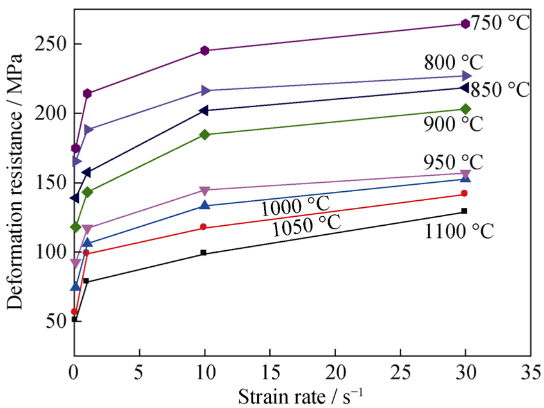

Fig. 4 Curves of strain rate versus deformation resistance

are finer. The ferrite and pearlite present band when deformed at 750 °C, while equiaxed feature when deformed at 950 and 1100 °C. This is because the dynamic recrystallization of austenite does not occur when deformed at 750 °C.

3.2.2 Effect of strain rate on deformation resistance

Effect of strain rate on deformation resistance was investigated at deformation degree of 0.4. According to curves of true stress–strain in Fig. 1, when the deformation degree is 0.4, deformation resistance values under different strain rates and deformation temperatures were calculated. The curves of deformation temperature and deformation resistance were drawn, as shown in Fig. 4.

As seen in Fig. 4, the deformation resistance does not monotonically increase with strain rate increasing, while there is an inflection point. When the strain rate is <1.0 s^{-1}, the deformation resistance rapidly increases with the increase in strain rate. There is an inflection point when the strain rate is 1.0 s^{-1}. When the strain rate is >1.0 s^{-1}, the increasing trend of deformation resistance becomes relatively slowly with strain rate increasing. But the overall situation is that deformation resistance increases with the increase in strain rate under a certain deformation temperature and deformation degree. The reasons are as follows [7, 16, 17]. (1) Work hardening and softening process simultaneously exist in the process of hot deformation. Since the increase in the strain rate results in that there is no enough time to complete the plastic deformation. The time to make dynamic recovery and recrystallization softening occurring in metal is relatively shorted, so the deformation cannot be adequately completed. Thus, the hardening rate is greater than the softening rate of deformation metal, and the deformation resistance increases. (2) A large amount of dislocation motion is required in the process of metal plastic deformation. When the strain rate increases, the speed of dislocation motion is accelerated. The shear stress of dislocation motion increases, and the deformation resistance also increases. (3) At the beginning of the deformation, the work hardening rate sharply increases with the increase in strain rate. Deformation energy by the metal plastic deformation can be mostly converted to heat when the amount of deformation exceeds a certain degree, and at the same time, the time of deformation is shorted, which makes that the heat cannot be dissipated. The temperature of metal increases due to the temperature effect so that the increasing trend of work hardening rate becomes gentler. (4) The changes of strain rate may also change the coefficient of friction, which influence the deformation resistance of metals.

3.2.3 Effect of deformation degree on deformation resistance

It can be seen from Fig. 1 that deformation resistance increases rapidly with the increase in deformation degree at the beginning of deformation stage. With the further increase in deformation degree, deformation resistance increases to a certain value, or appears relatively stable stress value without a peak value, or appears obvious peak value, and then reduces to a relatively stable value, or

Table 2 Regression coefficient of mathematical model for deformation resistance of tested sample

σ_0/MPa	a_1	a_2	a_3	a_4	a_5	a_6
133.238	−2.230658	2.889291	0.267954	−0.216007	0.373773	1.442272

appears peak value then decreases but without obvious stable value. The reasons are as follow [7, 18–20]: At the beginning of the deformation, with the increase in deformation degree, lattice distortion occurs in metal grains so that the density of crystal defects such as dislocation increases. With the increase in the interaction of moving dislocations, there will be produced pile up, jog, tangles, and other obstacles that hinder the dislocation movement and, as a result, the deformation resistance increases. With the increase in the deformation degree, dynamic recovery occurs, which causes a softening effect. So the part of work hardening is offset, making the increasing trend of deformation resistance become slowly. Finally, the value of deformation resistance reaches a stable value. Alternately, with further deformation, distortional energy produced by deformation can force the occurrence of dynamic recrystallization which makes the dislocation density reduce, and then the deformation resistance significantly decreases. The stress decreases to a minimum value until the round of recrystallization is completed. The stress finally reaches a stable value or continues to decrease, implying that recrystallization process could not be completed.

4 Mathematical model of deformation resistance

The research of deformation resistance model began in the 1950s. By comparative analysis of the mathematical model created by predecessors, the model of deformation resistance (σ) that comprehensively considers the influence factors of deformation resistance was established by Zhou and Guan [8] and has extensive applicability. The model was as below:

$$\sigma = \sigma_0 \exp(a_1 T + a_2)\dot{\varepsilon}^{a_3 T + a_4} \times a_6 \left(\frac{\varepsilon}{0.4}\right)^{a_5} - (a_6 - 1)\frac{\varepsilon}{0.4} \tag{1}$$

where σ_0 is the reference deformation resistance value in MPa, i.e., the deformation resistance value under the conditions of temperature of 1000 °C, deformation degree of $\varepsilon = 0.4$ and strain rate of $\dot{\varepsilon} = 10.0\ \text{s}^{-1}$; T is the deformation temperature in K; and a_1 to a_6 are the regression coefficients, which are determined based on the steel grades.

The model of deformation resistance adopted was established by Zhou and Guan [8]. Regression coefficients of deformation resistance constitutive equation was obtained by 1stOpt software using the Levenberg–Marquardt optimization algorithm carried out on the fitting of regression coefficients. The results are shown in Table 2. By substituting regression coefficients into Eq. (1), the mathematical model of deformation resistance for Fe–Mn–V–N alloy is:

$$\begin{aligned}\sigma =& 133.238 \exp\big(-2.230658T + \\ & 2.889291\big)\left(\frac{\dot{\varepsilon}}{10}\right)^{(0.267954T - 0.216007)} \times \\ & \left[1.442272\left(\frac{\varepsilon}{10}\right)^{0.373773} - (1.4442272 - 1)\frac{\varepsilon}{0.4}\right]\end{aligned} \tag{2}$$

Schematic diagram of comparison between calculated values and measured values of deformation resistance is shown in Fig. 5. As shown in Fig. 5, there is a certain deviation between calculated values and measured values. But generally speaking, the curve of calculated values has a good agreement with that of measured values.

According to regression theory, the residual standard deviation (S_y) is:

$$S_y = \sqrt{\frac{Q}{N - M - 1}} \tag{3}$$

where $Q = 2333925.32183$ is residual sum of squares, $N = 39034$ is the set number of experimental data, and $M = 6$ is undetermined number of regression coefficients. S_y is calculated to be 7.733.

When the confidence level (α) is 0.05, the t-distribution (t_α^N) namely $t_{0.05}^{39034}$ is 1.645 by looking over t-distribution table, then $t_{0.05}^{39034} \times S_y = 12.721$ MPa. The prediction accuracy of regression Eq. (2) is ($\sigma \pm 12.721$) MPa, i.e., 95 % the possibility of deformation resistance will fall in the range of $\sigma - 12.721 < \sigma < \sigma + 12.721$. The correlation coefficient (R) is 0.988317, so the fitting effect is better.

5 Conclusion

The deformation resistance of Fe–Mn–V–N alloy was investigated by thermal simulation experiment. Effect laws of different deformation parameters on deformation resistance were analyzed. When other conditions are constant, the deformation resistance decreases with the increase in deformation temperature, and the deformation resistance increases with the increase in strain rate and deformation degree. The mathematical model of deformation resistance

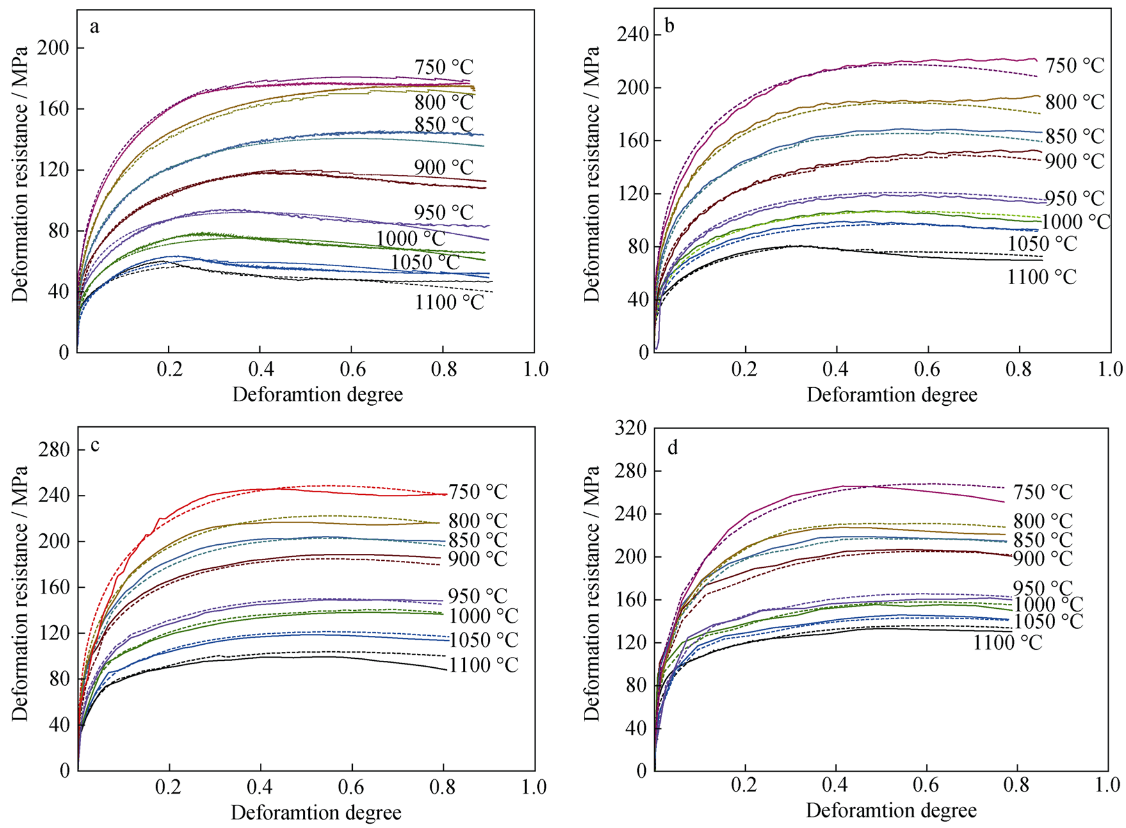

Fig. 5 Comparison between calculated values (dot lines) and measured values (solid lines) of deformation resistance at strain rates of **a** 0.1, **b** 1.0, **c** 10.0, and **d** 30.0 s^{-1}

for Fe–Mn–V–N alloy was established. There is a higher fitting precision between calculated values and measured values. The model can be used to calculate rolling force in actual production.

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