Research on Deformation Resistance Modeling for 316 stainless steel

Ningyu Du, Jinlong Fan, Hailun Xu

***Abstract*—This study focuses on developing a deformation resistance model for 316 stainless steel applied in rolling processes. Initially, rheological stress data under various temperatures, strain rates, and deformation degrees were obtained through hot compression tests, followed by an analysis of the influence of deformation parameters on the deformation resistance. A comprehensive model based on the Zhou-Guan framework was established via multivariate nonlinear regression of experimental data. Validation against experimental results and rolling production data confirmed the model's accuracy in predicting rolling force across diverse conditions. This work provides a foundation for optimizing stainless steel production processes and enhancing product quality.**

***Index Terms*—stainless steel, deformation resistance model, thermal deformation, stress-strain**

I. INTRODUCTION

316 stainless steel is widely used in shipbuilding, construction, and aerospace due to its corrosion and high-temperature resistance [1][2]. In industrial production, optimizing the manufacturing process to improve product yield and quality has always been a key concern [3]. With the advancement of computer technology, the rolling production of stainless steel has largely achieved automatic control, where the accuracy of the process model is crucial for ensuring product performance [3][5][6]. The parameters of the deformation resistance model are the core inputs to the process model, and their precision directly impacts the prediction accuracy of key parameters such as rolling force and rolling moment [7][8]. This, in turn, affects the selection of rolling mill equipment, process parameter development, and product quality control.

Existing models for predicting the behavior of untested steel grades based on chemical composition exhibit significant errors at low temperatures, limiting their utility in multi-pass hot rolling. However, comprehensive test data for many steels remain incomplete, and prediction methods based solely on chemical composition are still often employed for untested grades. Predictions obtained through such methods exhibit significant deviations under low-temperature conditions, failing to meet the requirements for predicting deformation resistance in hot rolling passes. Therefore, to enhance prediction accuracy, the deformation resistance model for 316 stainless steel needs further improvement.

In this study, the deformation behavior of 316 stainless steel was investigated using a Gleeble thermal simulation test system. The effects of deformation temperature, strain rate, and deformation degree on deformation resistance were analyzed. Subsequently, a deformation resistance model for 316 stainless steel was established based on classical constitutive theory and multivariate nonlinear regression of experimental data. The model was subsequently applied and verified using actual production data.

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II. EXPERIMENTAL PROGRAM

A. Experimental Material

The experimental steel was a hot-rolled 316 stainless steel plate provided by a steel company. The chemical composition of the material is shown in Table I, determined using a plasma emission spectrometer and a carbon and sulfur analyzer.

TABLE I
COMPOSITION OF EXPERIMENTAL STEEL (MASS FRACTION, %)

Element	C	Si	Mn	Cr	Ni	Mo	Fe
Content	0.041	0.46	1.62	17.53	12.2	2.55	Bal.

B. Thermal deformation test

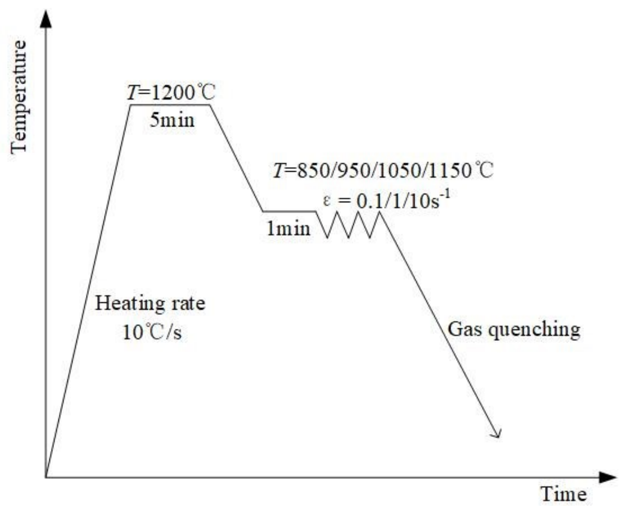

Fig. 1. The heating and deformation process of experimental steel

Several cylindrical samples with dimensions of φ8×12 mm were cut and processed from the hot-rolled stainless steel plate. Hot compressive deformation experimentation was performed on a Gleeble-1500 thermal-mechanical machine. The test process parameters are shown in Fig. 1. Samples were heated to 1200℃ firstly and held for 5 minutes to ensure uniformity of microstructure of the specimens before compression. Subsequently, the sample was slowly cooled to the target temperature, held for 1 minute for temperature homogenization, and then deformed. The experimental process involved four deformation temperatures (850℃, 950℃, 1050℃, and 1150℃), three typical deformation rates (0.1 s^{-1}, 1 s^{-1}, and 10 s^{-1}), and all the samples were deformed in compression with a total strain of 0.6.

III. RESULTS AND DISCUSSION

A. Stress-Strain Curve

Fig. 2(a) and (b) present the stress-strain curves of the experimental steel under different temperatures when the deformation rate $\dot{\varepsilon}$ is 0.1 s^{-1} and 1 s^{-1}, respectively. Fig. 2(c) and (d) show the stress-strain curves of the experimental steel at different deformation rates for temperatures T are 950℃ and 1050℃, respectively. As shown in Fig. 2(a) and (b), at a fixed strain rate, deformation rate, the deformation resistance of the experimental steel decreases with increasing temperature, and the curve shape transitions from work-hardening dominated behavior to dynamic recrystallization dominated behavior [9]. From Fig. 2(c) and (d), it is evident that at a fixed temperature, the deformation resistance increases with increasing strain rate, and the curve shape transitions from dynamic recrystallization dominated to work-hardening dominated [10]. This shift indicates that the experimental steel is more prone to dynamic recrystallization under conditions of low strain rate and high deformation temperature. The occurrence of dynamic recrystallization requires certain conditions, including sufficient deformation, appropriate temperature, and a low strain rate. At low strain rates, the material has sufficient time for dislocation movement and reorganization, promoting dynamic recrystallization. Conversely, at high strain rates, dislocation accumulation accelerates, enhancing work-hardening. Under these conditions, the energy and time required for dynamic recrystallization are insufficient, inhibiting its occurrence [11].

B. Effect of temperature on deformation behavior

Deformation temperature is a crucial parameter in material processing and significantly influences deformation behavior. Investigations on the deformation behavior of 201 and 430 stainless steels, as well as low-alloy high-strength steels, have demonstrated a strong negative correlation between deformation resistance and deformation temperature [12][13]. Research on Q345D steel has shown that, at a fixed deformation rate, the natural logarithm of deformation resistance exhibits a nearly linear decrease with increasing deformation temperature, i.e., the natural logarithm of stress, lnσ, has a linear functional relationship with deformation temperature, T [14][15].

In this study, based on experimental results, the relationship curves between lnσ and deformation temperature

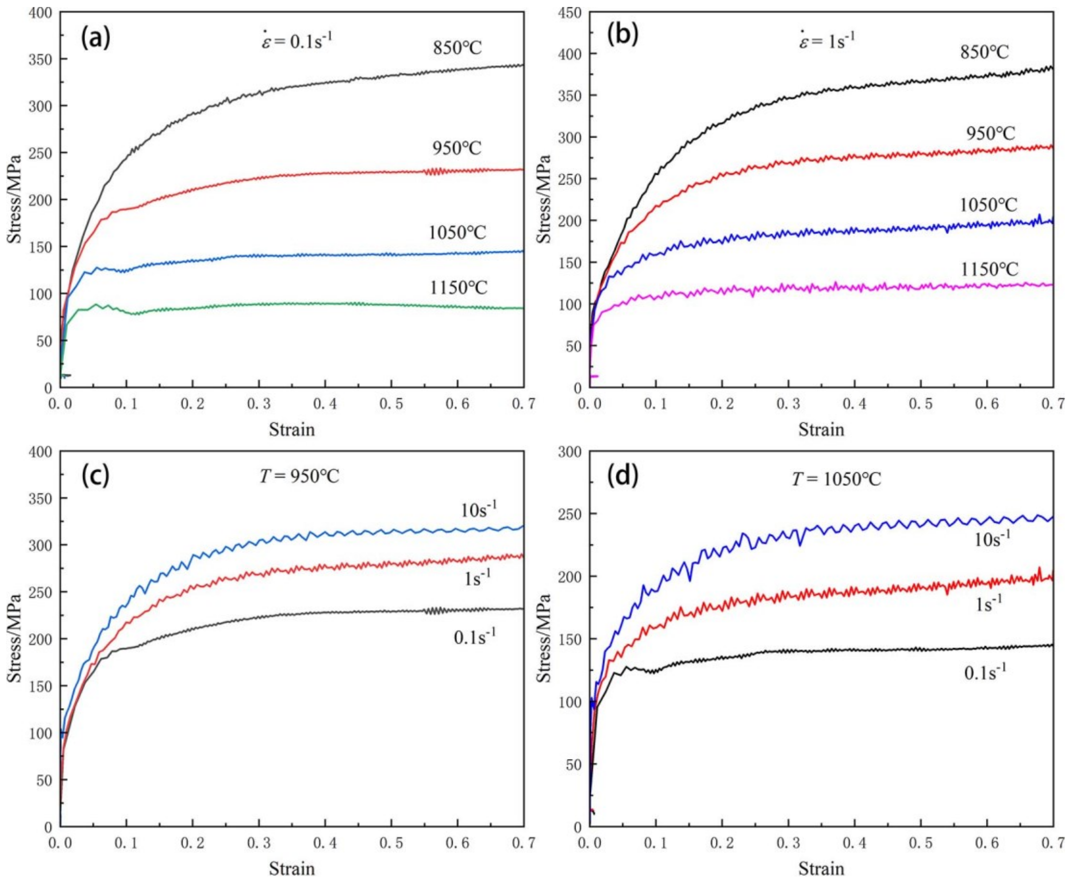

Fig. 2. Stress-strain curves: (a) deformation rate $\dot{\varepsilon}$ = 0.1 s^{-1}; (b) deformation rate $\dot{\varepsilon}$ = 1 s^{-1}; (c) deformation temperature T = 950℃; (d) deformation temperature T = 1050℃

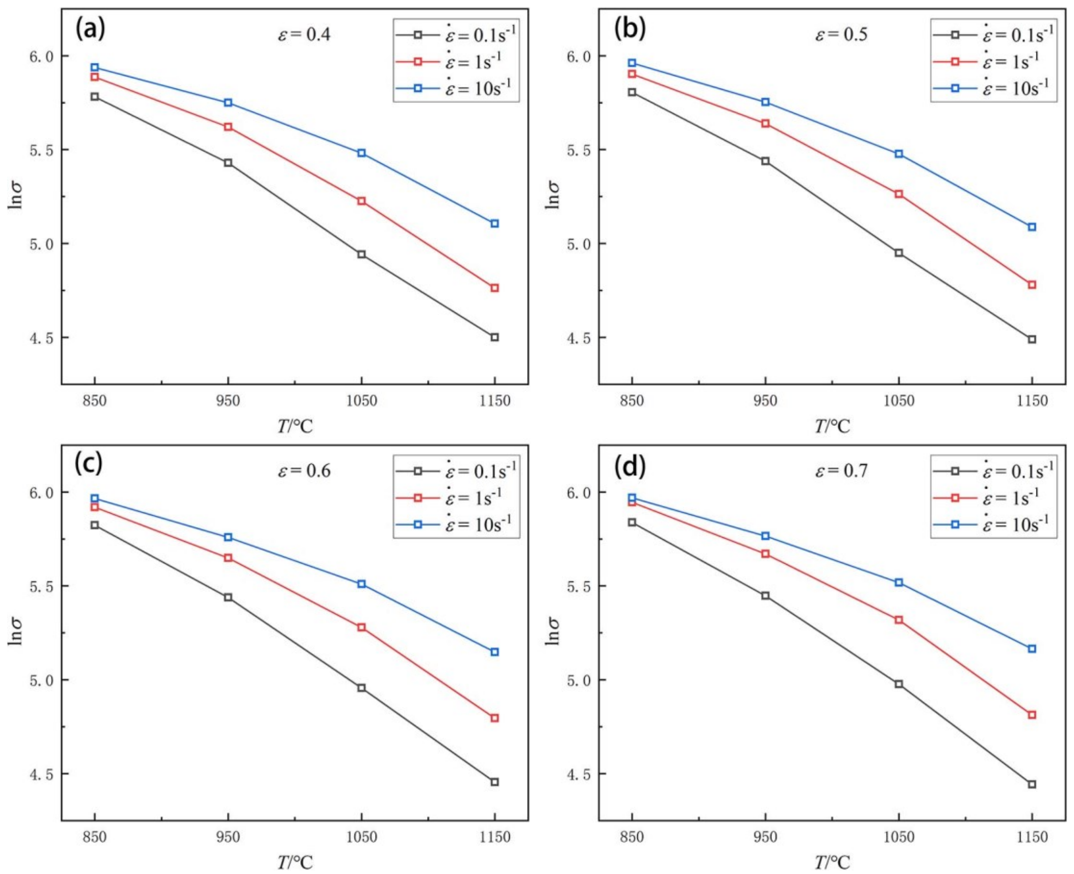

Fig. 3. The relation between lnσ and T with strain ε of (a) 0.4, (b) 0.5, (c) 0.6, (d) 0.7

T at different deformation rate for 316 stainless steel at strain ε of 0.4, 0.5, 0.6, and 0.7 are plotted in Fig. 3. It is observed that lnσ decreases with increasing temperature T, but not linearly. Instead, the rate of decrease of lnσ accelerates with rising temperature T. This behavior is attributed to the increase in thermal vibration amplitude of metal atoms and decrease in interatomic bonding strength at higher temperatures, facilitating atomic slip. Additionally, new slip systems are

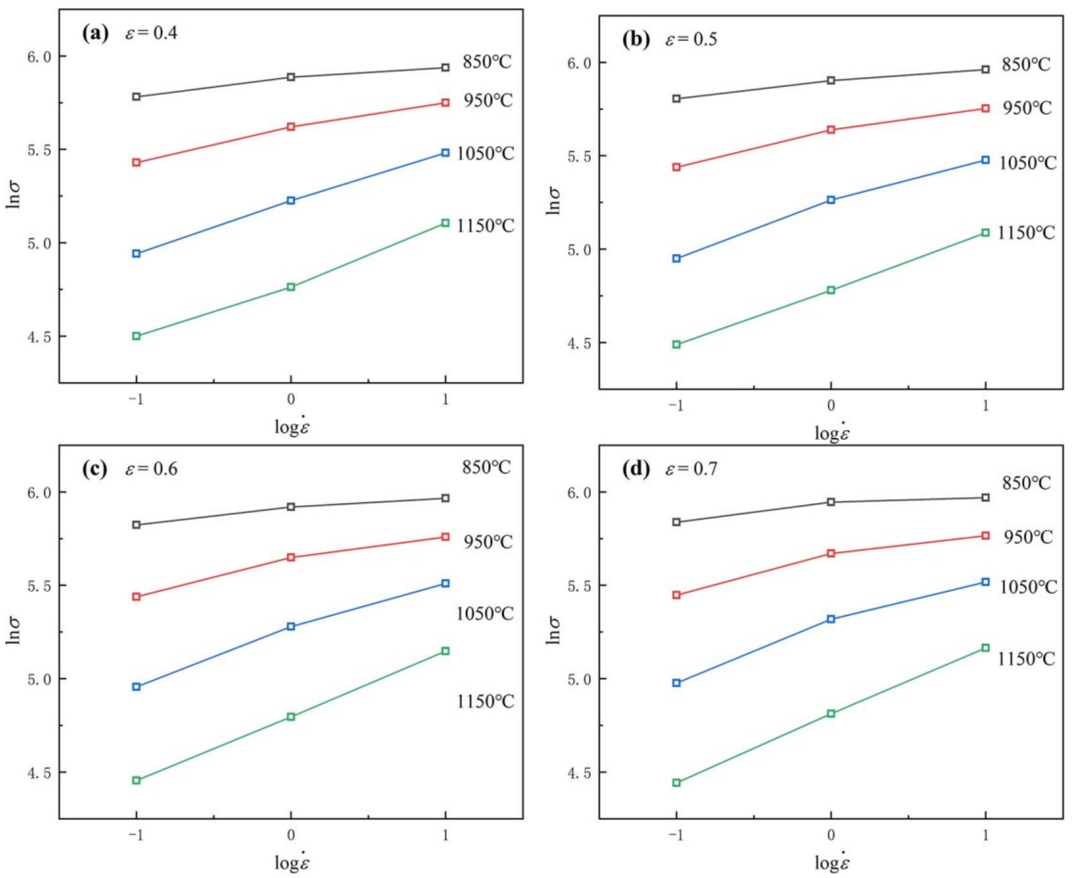

Fig. 4. The relationship between lnσ and log$\dot{\varepsilon}$ with the strain of (a) 0.4, (b) 0.5, (c) 0.6, (d) 0.7

activated, and dislocation movement (including slip, climb, and cross-slip) becomes easier [16][17]. These mechanisms facilitate plastic deformation, thereby reducing deformation resistance. The dependence of deformation resistance on temperature is nonlinear due to its complex dependence on multiple factors such as temperature and strain rate.

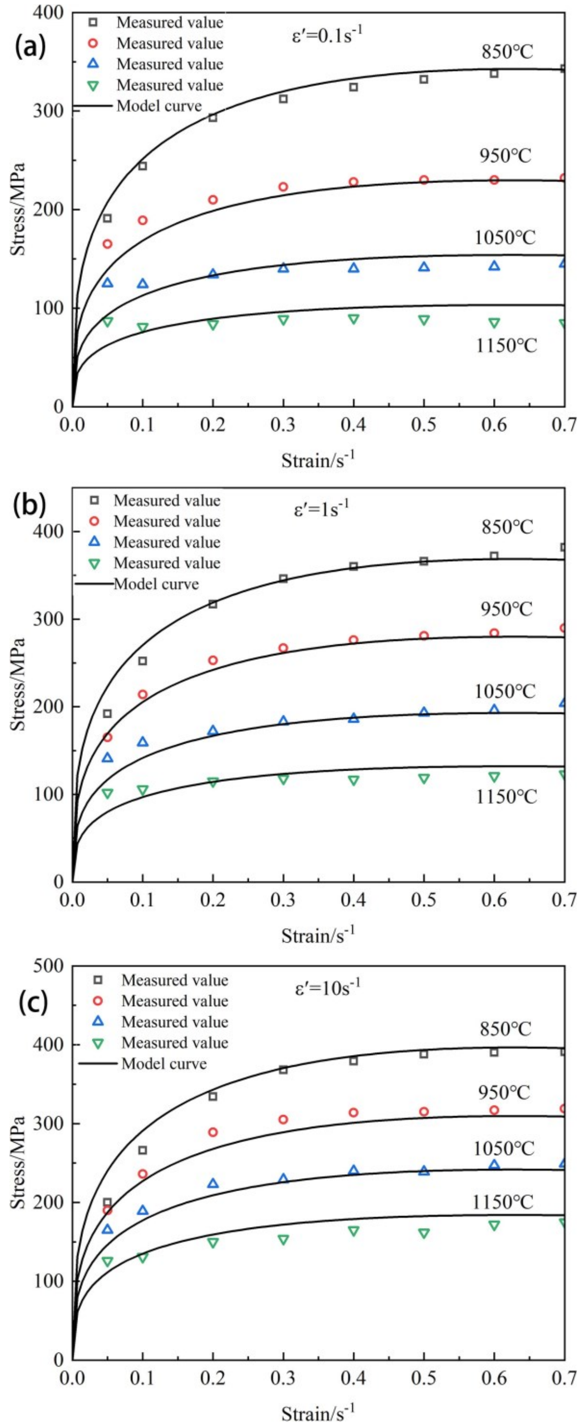

Fig. 5. Comparison between the predicted curves of the deformation resistance model and the measured values

C. Effect of deformation rate on deformation behavior

Deformation rate is another important parameter affecting the deformation process, microstructure evolution, and mechanical properties of the material. At constant deformation temperature, higher strain rates result in greater deformation resistance [12][18]. It has also been demonstrated in the literature that the logarithmic value of deformation resistance increases linearly with the logarithmic value of deformation rate at the same deformation temperature [13].

TABLE II
REGRESSION COEFFICIENTS OF DEFORMATION RESISTANCE MODEL FOR 316 STAINLESS STEEL

Coefficient	a_1	a_2	a_3	a_4	a_5	a_6
Value	-2.475	3.110	0.331	-0.340	0.333	1.327

In this study, the relationship between the natural logarithm of deformation resistance, lnσ, and the logarithm of deformation rate, log$\acute{\varepsilon}$, are plotted for the experimental steels at different temperature and strain ε of 0.4, 0.5, 0.6, and 0.7, as shown in Fig. 4. The results confirm that the value of lnσ increases with increasing log$\acute{\varepsilon}$, consistent with findings for other steels. For deformation temperatures between 850°C and 1050°C,Fig. 4 shows that the increase of lnσ is more pronounced when the deformation rate rises from 0.1 s^{-1} to 1 s^{-1}compared to the increase from 1 s^{-1} to 10 s^{-1}, deviating from a purely linear relationship. However, when the deformation temperature is 1150°C, the relationship between lnσ and log$\acute{\varepsilon}$ is approximately linear. As mentioned above, during the deformation of metal, dislocation locking, recovery and recrystallization occur simultaneously. When the deformation rate is higher, the locking rate of dislocation is also higher, and the degree of work hardening dominates over recrystallization softening. Therefore, when the deformation rate $\dot{\varepsilon}$ increases, σ and lnσ increase. An increase in the deformation rate typically leads to a greater amount of heat generated during deformation, which in turn raises the temperature of the material. This temperature effect can promote dynamic recrystallization, thereby reducing the deformation resistance [19]. Since recrystallization is highly temperature-dependent and favored at higher temperatures, the trend of lnσ versus log$\acute{\varepsilon}$ varies with deformation temperature.

IV. MODEL OF DEFORMATION RESISTANCE

A. Modeling

The main factors influencing deformation resistance are temperature, deformation rate, and deformation degree. Their relationship is commonly expressed as [12]:

$$\sigma = f(T, \varepsilon, \varepsilon', x\%)$$

Where σ is the deformation resistance (MPa); T is the deformation temperature (K); ε is the true strain; ε' is the deformation rate (s^{-1}); and x% indicates the influence of composition and microstructure of experimental steel. For the specific 316 stainless steel studied here, the composition is fixed, allowing x% to be neglected during model establishment.

Among constitutive models for deformation resistance, the Zhou-Guan model is widely applied [20][21]:

$$\sigma = \sigma_0\, exp\left(\frac{a_1 T}{1000} + a_2\right)\left(\frac{\dot{\varepsilon}}{10}\right)^{\left(\frac{a_3 T}{1000} + a_4\right)} \times \left[a_6\left(\frac{\varepsilon}{0.4}\right)^{a_5} - (a_6 - 1)\left(\frac{\varepsilon}{0.4}\right)\right]$$

Where σ_0 is the reference deformation resistance (MPa). Based on experimental data, σ_0 of 316 stainless steel was set to 277. a_1, a_2, a_3, a_4, a_5, a_6 are regression coefficients.

Based on the experimental data of hot compressive deformation, the regression coefficients are obtained by regression analysis which was performed using Origin software. The values of a_1, a_2, a_3, a_4, a_5, a_6 are shown in Table II. Error analysis was conducted on the fitting results, and the correlation coefficient R^2 was 0.987, indicating a high accuracy level.

Substituting the regression coefficients into the model, the deformation resistance model for 316 stainless steel can be obtained as:

$$\sigma = 277\,exp(-0.002475T + 3.110)\,(\frac{\acute{\varepsilon}}{10})^{(0.000331T-0.340)} \times [1.327\left(\frac{\varepsilon}{0.4}\right)^{0.333} - 0.327\left(\frac{\varepsilon}{0.4}\right)]$$

B. Model validation

Predicted stress-strain curves were generated using the above model and compared with experimental data points. The comparison is shown in Fig. 5. Overall, the model exhibits high prediction accuracy for strains exceeding 0.2. Below ε = 0.2, predicted values deviate significantly from measurements, rendering the model less applicable in this range. At a strain rate of 0.1 s^{-1}, model predictions agree well with data at 850℃ and 950℃. At 1050℃ or 1150℃, predictions are slightly higher than measured values. At $\acute{\varepsilon}$ = 1 s^{-1}, predictions are accurate at 850℃, 950℃, and 1050℃. At 1150℃, predictions are marginally higher. At $\acute{\varepsilon}$ = 10 s^{-1}, predictions match data well at 850℃ and 1050℃. At 950℃, predictions are slightly lower than measurements, with accuracy improving at strains > 0.5. At 1150℃, predictions are again slightly higher than measurements.

V. Applications in Calculation of Rolling

Accurate rolling models are crucial for steel rolling simulations, as they provide the theoretical foundation for predicting key parameters like rolling force and rolling moment, enabling optimal process control and product quality [22]. Such models are essential for optimizing rolling mill design, developing efficient process parameters, and enhancing production efficiency and competitiveness.

To validate the applicability of the developed deformation resistance model, production data (including billet dimensions, rolling passes, rolling speed, rolling temperature, rolling force, and roll diameter) were collected from a stainless-steel hot rolling line. These parameters served as inputs to calculate the deformation resistance and subsequently the rolling force for 316 stainless steel in various passes. The calculated rolling force (CRF) was compared with measured rolling force (MRF), as listed in Table III.

TABLE III
Comparison of Rolling Production Data with Calculated Data

RP	Thi.	Wid.	Red.	Tem.	DR	CRF	MRF	Dev.
	mm	mm	mm	℃	MPa	kN	kN	%
	220.0	1245		1050				
1	172.0	1047	48.0	1044	192.9	19233	17868	7.6
2	123.7	1054	48.3	1048	213.2	27486	25388	8.3
3	82.0	1051	41.7	1058	225.4	30292	28716	5.5
4	53.9	1050	28.1	1078	223.8	28870	27333	5.6
5	37.4	1057	16.5	1130	201.3	25236	24300	3.9

Note: RP – Rolling passes, Thi. – Thickness, Wid. – Width, Red. - Reduction, Tem. – Temperature, DR – Deformation resistance, CRF – Calculated rolling force, MRF – Measured rolling force, Dev. – Deviation.

Table III shows that the deviation between CRF and MRF is within 10%. This accuracy level is sufficient for selecting rolling mill drives and designing production lines. It is important to note that temperature is a critical parameter for rolling force calculation. The temperatures used here were measured on the production line. However, if temperatures are predicted by empirical models, accuracy may degrade.

VI. Summary and Outlook

The deformation behavior of 316 stainless steel under different temperatures and strain rates was analyzed through thermal simulation experiments. Based on the experimental data, a deformation resistance model was developed using nonlinear regression within the Zhou-Guan framework. Validation confirmed the model's good predictive capability, providing a basis for stainless steel production line design and rolling process parameter optimization.

Future research on rolling models remains vital. Efforts should focus on integrating advanced computational techniques, such as artificial intelligence and machine learning, to enhance model accuracy and adaptability. Additionally, incorporating more comprehensive material behavior, including microstructural evolution and phase transformations, will better predict steel product performance. These advancements will improve production efficiency and facilitate the development of high-performance steels for specific applications.

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