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PREDICTION OF THE INFLUENCE OF ROLLING PROCESS PARAMETERS ON THE MECHANICAL PROPERTIES OF RARE-EARTH-CONTAINING ALUMINUM ALLOYS

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Abstract: This study investigated the effects of rolling temperature and total reduction ratio on the mechanical properties of a rare-earth-containing Al-Mg-Si alloy, aiming to optimize the strength–ductility balance during thermomechanical processing. Rolling experiments were conducted under different temperatures and reduction ratios, and the resulting mechanical properties were evaluated by tensile testing and hardness measurements. Optical microscopy, scanning electron microscopy, and electron backscatter diffraction were employed to characterize microstructural evolution and to clarify the process–microstructure–property relationship. The results showed that increasing the total reduction ratio significantly improved yield strength, ultimate tensile strength, and hardness, but reduced elongation, whereas increasing the rolling temperature weakened the strengthening effect while enhancing ductility. The highest strength was achieved at 25 °C with a 70% reduction ratio, while the best elongation was obtained at 400 °C with a 30% reduction ratio. A favorable strength–ductility balance was realized at 200 °C and 50% reduction. In addition, quadratic regression and random forest models were developed to predict mechanical properties, and the random forest model exhibited higher accuracy. This work establishes a process–microstructure–property framework and highlights machine-learning-assisted prediction as a useful strategy for optimizing rare-earth-containing aluminum alloys.
Keywords: Rolling process parameters; Rare-earth-containing aluminum alloy; Mechanical properties; Predictive model

1 INTRODUCTION

Aluminum alloys are widely used in aerospace, rail transportation, automotive manufacturing, and electronics industries because of their low density, high specific strength, good corrosion resistance, and excellent processability[1-2]. With the increasing demand for lightweight structures and high-performance manufacturing, the synergistic regulation of microstructure and properties through alloy design and thermomechanical processing has become a major topic in the field of materials processing[3-4]. In recent years, rare-earth elements have been extensively introduced into aluminum alloys as microalloying additions due to their unique atomic size effects and high chemical activity. Previous studies have shown that appropriate additions of rare-earth elements can refine grains, modify the distribution of secondary phases, suppress recrystallization, and consequently improve the strength, ductility, and thermal stability of aluminum alloys to a certain extent. As a result, rare-earth-containing aluminum alloys have attracted increasing attention as a promising class of lightweight structural materials.

To date, research on rare-earth-containing aluminum alloys has mainly focused on the effects of rare-earth additions on as-cast microstructures, precipitation behavior, and overall mechanical properties, whereas relatively limited attention has been paid to microstructural evolution during subsequent plastic deformation[5-6]. As one of the most commonly used forming routes for aluminum alloy sheets and plates, rolling involves process parameters such as temperature, reduction ratio, and pass schedule, all of which strongly affect dislocation accumulation, grain deformation, recrystallization behavior, and texture evolution, and thus ultimately determine the mechanical properties of the processed alloy[7]. For rare-earth-containing aluminum alloys, the presence of rare-earth phases or dispersoids may further alter the deformation response and microstructural stability during rolling, making the process-microstructure-property relationship even more complicated. Although some studies have reported the influence of rare-earth elements and rolling conditions on the microstructure and properties of aluminum alloys, most of them remain largely descriptive, and systematic investigations into the quantitative relationship among rolling parameters, microstructural characteristics, and mechanical performance are still insufficient, particularly in terms of property prediction and process optimization.

In view of this, the present work focuses on a rare-earth-containing aluminum alloy and systematically investigates the influence of rolling process parameters on its mechanical properties. By designing different rolling conditions and combining mechanical testing with microstructural characterization, the effects of rolling temperature, reduction ratio, and related process variables on grain evolution, recrystallization behavior, and overall microstructural features are analyzed in detail. On this basis, the intrinsic relationship between rolling parameters and mechanical performance is further clarified. In addition, a predictive model is developed to evaluate the influence of rolling process parameters on the mechanical properties of rare-earth-containing aluminum alloys, with the aim of providing theoretical support for process optimization and property tailoring of this type of alloy.

2 MATERIALS AND METHODS

2.1 Material Preparation

The investigated material was a rare-earth-containing aluminum alloy based on the Al-Mg-Si system, with Ce selected as the rare-earth microalloying element. The nominal chemical composition of the alloy was Al-0.95Mg-0.72Si-0.25Fe-0.20Ce (wt.%). The alloy was prepared by melting commercially pure aluminum (99.9 wt.%) together with Al-20Mg, Al-20Si, and Al-10Ce master alloys in an electric resistance furnace. During melting, a covering flux was used to reduce oxidation, and the melt was mechanically stirred for 5 min after complete melting to improve compositional uniformity. The melt was held at 750 °C for 15 min and subsequently degassed by argon purging for 8 min. The molten alloy was then poured into a steel mold preheated to 220 °C to produce ingots with dimensions of 120 mm × 80 mm × 25 mm.

To reduce chemical segregation and homogenize the as-cast microstructure, the ingots were subjected to a homogenization treatment at 520 °C for 8 h, followed by air cooling to room temperature. After homogenization, the ingots were machined into rectangular slabs with dimensions of 100 mm × 60 mm × 10 mm for rolling experiments. Prior to rolling, the surface oxide scale and machining marks were removed by grinding with SiC papers to ensure stable contact conditions during rolling deformation.

The actual chemical composition of the alloy was measured by optical emission spectroscopy, and the results were found to be in good agreement with the nominal composition. The homogenized alloy was used as the initial material condition, and its microstructure was characterized prior to rolling in order to establish a reference state for subsequent analysis.

2.2 Rolling Process Design

Rolling experiments were carried out on a laboratory-scale two-high rolling mill with a roll diameter of 180 mm. To systematically investigate the influence of rolling parameters on the mechanical properties of the rare-earth-containing aluminum alloy, two major process variables were selected, namely rolling temperature and total reduction ratio. The rolling temperatures were set at 25 °C, 200 °C, and 400 °C, representing cold rolling, warm rolling, and hot rolling conditions, respectively. The total reduction ratios were designed as 30%, 50%, and 70%. The experimental matrix therefore consisted of nine groups of rolling conditions.

For specimens subjected to warm rolling and hot rolling, the slabs were preheated in a resistance furnace at the target temperature for 20 min before deformation to ensure uniform temperature distribution. During multi-pass rolling, the specimens were reheated for 5 min between adjacent passes to minimize temperature loss. For cold rolling, no preheating treatment was applied. The rolling direction was kept constant throughout the entire process. The roll speed was maintained at 0.25 m/s. To avoid excessive deformation per pass and edge cracking, the single-pass reduction was controlled at approximately 8-12%, depending on the deformation condition, until the target total reduction was achieved. The time interval between consecutive passes was controlled within 20 s.

After rolling, all specimens were air cooled to room temperature. The final thickness of each rolled sheet was measured using a digital micrometer with an accuracy of 0.001 mm, and the actual reduction ratio was calculated according to the thickness change. In order to ensure repeatability, three rolled sheets were prepared under each rolling condition.

2.3 Mechanical Testing

The mechanical properties of the rolled sheets were evaluated by room-temperature tensile testing and Vickers microhardness measurements. Flat dog-bone tensile specimens were machined from the rolled sheets with the tensile axis parallel to the rolling direction. The tensile specimen geometry followed the ASTM E8 standard for subsize sheet specimens, with a gauge length of 25 mm, a gauge width of 6 mm, and a thickness corresponding to the final rolled sheet thickness.

Tensile tests were performed on a universal testing machine at room temperature using a crosshead speed of 1 mm/min, corresponding to an initial strain rate of approximately 6.7 × 10^-4 s^-1. For each rolling condition, three parallel tensile specimens were tested, and the average values of yield strength (YS), ultimate tensile strength (UTS), and elongation to fracture (EL) were reported. The standard deviation was also calculated to evaluate data reproducibility.

To further understand the fracture behavior under different rolling conditions, the fracture surfaces of selected tensile specimens were examined by scanning electron microscopy. The fracture morphology, including dimple size, secondary cracking, and local brittle features, was used to analyze the deformation and damage mechanisms associated with different processing conditions.

Microhardness tests were conducted on the RD-ND section of each rolled specimen using a Vickers hardness tester under a load of 200 g and a dwell time of 15 s. For each specimen, ten indentations were made at different positions away from the edges and obvious second-phase particles, and the average hardness value was determined. The hardness results were used as supplementary evidence to assess the effects of work hardening and grain refinement.

2.4 Microstructural Characterization

The microstructures before and after rolling were characterized using optical microscopy (OM), scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD). Metallographic samples were sectioned along the rolling direction-normal direction (RD-ND) plane. The samples were ground with SiC papers from 400 to 2000 grit and then polished using diamond suspensions of 3 μm and 1 μm. Final polishing for EBSD analysis was performed using colloidal silica for 30 min to obtain a deformation-free surface.

Optical microscopy was employed to observe the general morphology of grains and deformation bands after etching with Keller's reagent. SEM observations were conducted using a field-emission scanning electron microscope operated at 15 kV to examine the morphology and distribution of second-phase particles and Ce-containing intermetallic compounds. Energy-dispersive spectroscopy was further used to analyze the local elemental distribution of rare-earth-rich phases and coarse particles.

EBSD characterization was performed to quantify grain size, grain boundary distribution, recrystallization fraction, and texture evolution under different rolling conditions. The EBSD scans were acquired with a step size of 0.5 μm for moderately deformed samples and 0.3 μm for heavily deformed samples. The data were processed using OIM Analysis software. Boundaries with misorientation angles between 2° and 15° were defined as low-angle grain boundaries (LAGBs), while boundaries with misorientation angles greater than 15° were considered high-angle grain boundaries (HAGBs). Recrystallized, substructured, and deformed regions were identified based on grain orientation spread values. In addition, inverse pole figure maps and pole figures were used to analyze texture development during rolling.

For representative samples, X-ray diffraction was also carried out using Cu Kα radiation with a scanning range from 20° to 90° to identify the phase constitution and evaluate crystallographic texture evolution. These characterization methods provided microstructural evidence for interpreting the variation in mechanical properties under different rolling conditions.

2.5 Predictive Modeling Method

To quantitatively describe the influence of rolling process parameters on the mechanical properties of the rare-earth-containing aluminum alloy, a predictive model was established based on the experimental data. The input variables included rolling temperature and total reduction ratio. In addition, selected microstructural descriptors, including average grain size, recrystallization fraction, and HAGB fraction, were introduced into the model as auxiliary variables to improve the physical relevance of the prediction. The output variables were yield strength, ultimate tensile strength, and elongation.

Before model development, all data were normalized using min-max scaling to eliminate the influence of dimensional differences among the variables. A second-order polynomial regression model was first established to describe the main effects and interaction effects of rolling temperature and reduction ratio on the mechanical properties[8]. This regression model can be expressed as follows:

$$Y=\beta_0+\beta_1 T+\beta_2 R+\beta_3 TR+\beta_4 T^2+\beta_5 R^2 \tag{1}$$

where Yrepresents the target mechanical property, $T$is the rolling temperature, $R$is the total reduction ratio, and $\beta_i$are the regression coefficients.

To further evaluate the nonlinear predictive capability, a random forest regression model was also developed for comparison. The dataset was randomly divided into a training set and a test set at a ratio of 80:20. Owing to the limited number of samples, five-fold cross-validation was employed during model training to reduce the risk of overfitting. The performance of the predictive models was assessed using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE).

In addition, feature importance analysis was performed in the random forest model to identify the dominant variables controlling the tensile properties. The comparison between experimental values and model predictions was used to verify the reliability of the proposed process-property relationship and to clarify the relative contributions of rolling parameters and microstructural features.

2.6 Statistical Analysis

All experimental results are presented as mean ± standard deviation. Statistical analysis was carried out using one-way analysis of variance (ANOVA), and differences were considered statistically significant at $p < 0.05$. The statistical results were further used to verify whether the variations in mechanical properties and microstructural parameters under different rolling conditions were significant. This analysis also provided a basis for screening effective variables for the predictive model.

3 RESULTS AND ANALYSIS

3.1 Effects of Rolling Parameters on Mechanical Properties

Table 1 summarizes the tensile properties, hardness, and representative microstructural parameters of the rare-earth-containing Al-Mg-Si alloy processed under different rolling conditions. It can be seen that both rolling temperature and total reduction ratio exerted significant influences on the mechanical response of the alloy. In general, increasing the reduction ratio led to a continuous increase in yield strength, ultimate tensile strength, and hardness, whereas elongation decreased progressively. By contrast, increasing the rolling temperature reduced the strengthening effect but improved the plastic deformation capability of the alloy.

Table 1 Mechanical Properties and Representative Microstructural Parameters under Different Rolling Conditions

Rolling temperature (°C)	Total reduction (%)	YS (MPa)	UTS (MPa)	EL (%)	HV0.2	Average grain size (μm)	Recrystallization fraction	HAGB fraction
25	30	238	286	13.4	91.2	41.8	0.18	0.36
25	50	266	318	10.1	103.6	26.4	0.11	0.28
25	70	294	347	7.2	116.4	14.9	0.05	0.19
200	30	224	279	16.8	85.4	48.6	0.32	0.44
200	50	252	309	14.9	94.7	39.1	0.41	0.52
200	70	271	328	11.8	102.5	27.8	0.29	0.39
400	30	206	262	19.3	79.6	62.5	0.57	0.61
400	50	221	276	17.6	83.8	58.4	0.63	0.66
400	70	233	289	14.2	88.7	51.3	0.54	0.59

The evolution of yield strength with rolling reduction at different temperatures is shown in Figure 1. At all rolling temperatures, the yield strength increased monotonically with increasing total reduction, indicating that strain accumulation and grain subdivision played dominant roles in strengthening. The highest yield strength, 294 MPa, was achieved at 25 °C and 70% reduction, whereas the lowest value, 206 MPa, was observed at 400 °C and 30% reduction. This result suggests that low-temperature rolling retained a larger amount of deformation-induced stored energy and suppressed recovery, thereby producing stronger strain hardening.

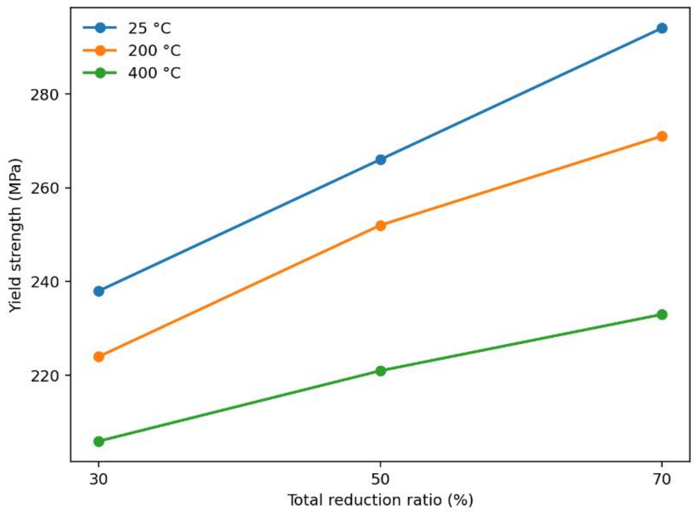

Figure 1 Yield Strength as a Function of Total Reduction Ratio under Different Rolling Temperatures

A similar trend was observed for ultimate tensile strength, as shown in Figure 2. The UTS increased from 286 MPa to 347 MPa when the total reduction ratio increased from 30% to 70% under cold rolling conditions. Under warm rolling at 200 °C, the alloy exhibited intermediate strength levels, with a UTS of 309 MPa at 50% reduction and 328 MPa at 70% reduction. Under hot rolling at 400 °C, the UTS remained comparatively low, which can be attributed to the enhanced dynamic recovery and partial recrystallization during deformation. These processes reduced dislocation density and weakened the work-hardening contribution.

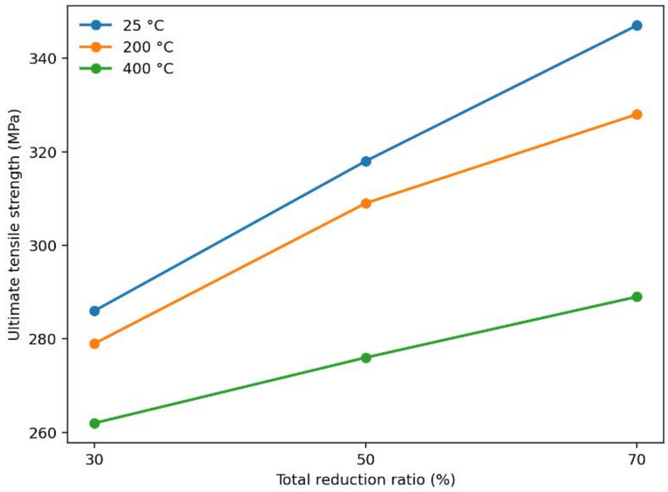

Figure 2 Ultimate Tensile Strength as a Function of Total Reduction Ratio under Different Rolling Temperatures

In contrast to the strength evolution, the elongation showed a decreasing trend with increasing reduction ratio, as illustrated in Figure 3. The highest elongation, 19.3%, was obtained at 400 °C and 30% reduction, while the lowest value, 7.2%, was recorded at 25 °C and 70% reduction. This indicates that excessive deformation at low temperature significantly reduced the plastic accommodation capacity of the alloy. Nevertheless, the specimen rolled at 200 °C with 50% reduction maintained a relatively favorable balance between strength and ductility, exhibiting a UTS of 309 MPa and an elongation of 14.9%. This condition may therefore be regarded as a promising process window for obtaining a balanced mechanical performance.

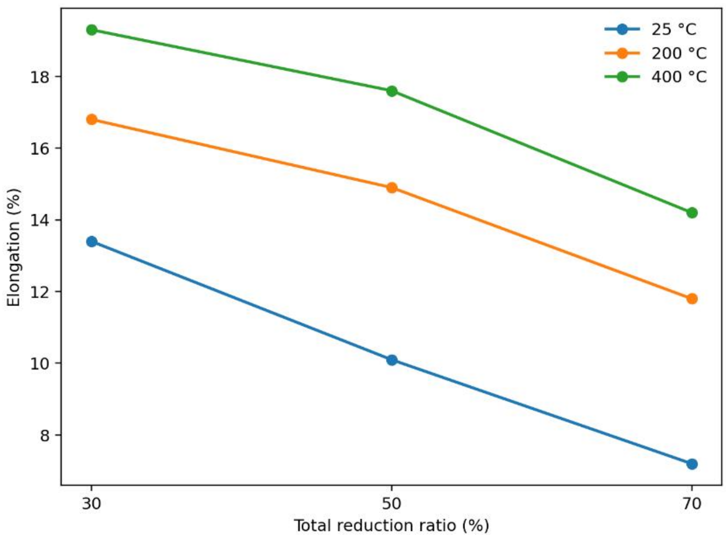

Figure 3 Elongation as a Function of Total Reduction Ratio under Different Rolling Temperatures

The hardness evolution further supports the tensile results. As shown in Figure 4, hardness increased with reduction ratio and decreased with rolling temperature. The maximum hardness of 116.4 HV0.2 was measured under the 25 °C-70% condition, which is consistent with the highest strength level in Table 1. Since hardness is sensitive to both dislocation density and microstructural refinement, this result confirms that low-temperature heavy rolling effectively strengthened the alloy through combined work hardening and grain refinement.

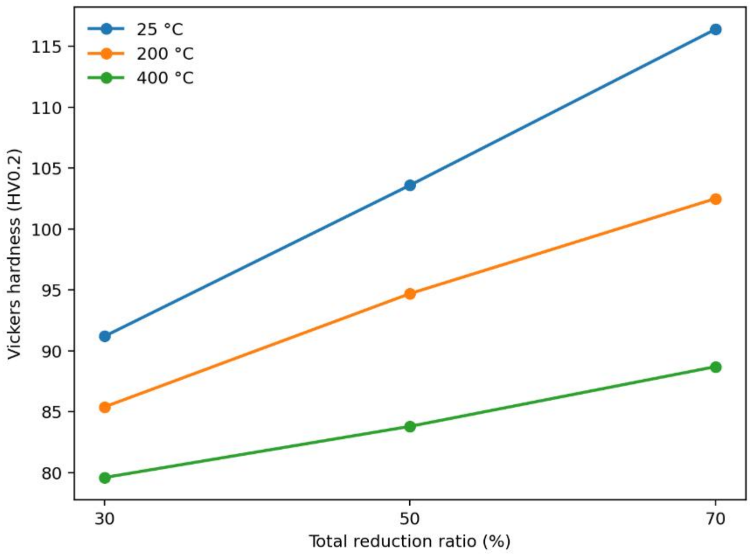

Figure 4 Vickers Hardness as a Function of Total Reduction Ratio under Different Rolling Temperatures

Overall, the mechanical results indicate that the effects of rolling parameters were not simply linear. Low rolling temperature and high reduction ratio favored strength enhancement, whereas high temperature promoted ductility. From an engineering perspective, the 200°C-50% condition appears to offer the most favorable strength-ductility synergy among the investigated processing routes.

3.2 Microstructure Evolution under Different Rolling Conditions

The representative microstructural parameters listed in Table 1 show that the average grain size decreased markedly with increasing reduction ratio, particularly under cold rolling conditions. When the rolling temperature was 25 °C, the grain size was refined from 41.8 μm at 30% reduction to 14.9 μm at 70% reduction, demonstrating a pronounced deformation-induced grain subdivision effect. At elevated temperatures, the grain refinement effect was less significant because thermal activation facilitated recovery and grain boundary migration.

The recrystallization fraction and HAGB fraction exhibited clear temperature dependence. The alloy rolled at 400 °C showed relatively high recrystallization fractions, ranging from 0.54 to 0.63, whereas the corresponding values at 25 °C remained below 0.20. This indicates that high-temperature rolling activated recrystallization and boundary rearrangement more effectively. The HAGB fraction followed a similar trend, suggesting that recovery and recrystallization promoted the transformation of deformation substructures into more stable grain boundary configurations.

To further clarify the microstructure-property relationship, the variation in ultimate tensile strength as a function of average grain size is plotted in Figure 5. A clear inverse correlation can be identified: specimens with smaller grain size generally exhibited higher UTS. The 25 °C-70% specimen, which possessed the finest grain structure, showed the highest tensile strength, whereas the 400 °C-30% specimen, characterized by the coarsest grains, displayed the lowest UTS. This observation suggests that grain refinement remained one of the primary strengthening mechanisms under the present processing conditions.

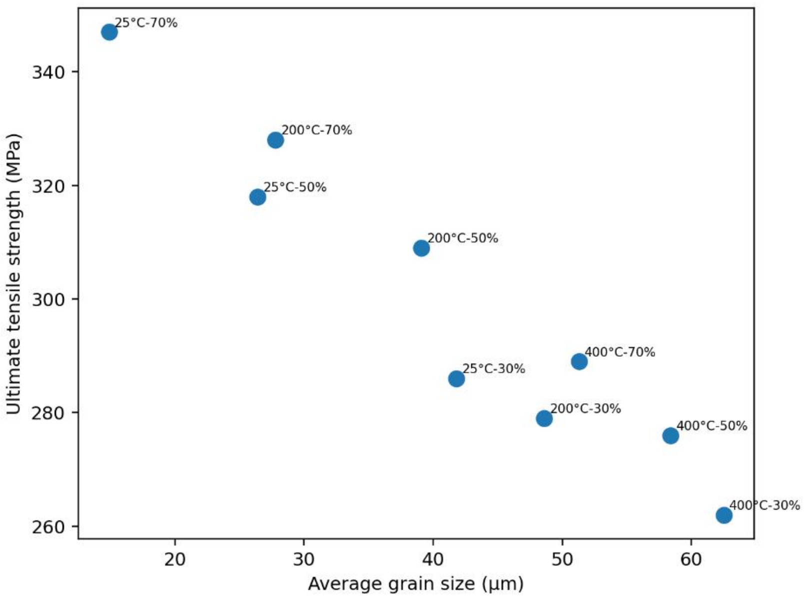

Figure 5 Correlation between Average Grain Size and Ultimate Tensile Strength

However, grain size alone cannot fully explain the mechanical response. For example, the 200 °C-50% condition did not exhibit the smallest grain size, yet it still achieved a relatively high tensile strength together with acceptable ductility. This implies that an appropriate combination of moderate grain refinement, retained substructure, and controlled recrystallization may be more beneficial than extreme deformation alone. In other words, the mechanical behavior of the alloy was governed by the combined effects of grain refinement, work hardening, and recrystallization evolution.

From the perspective of microstructural stability, the presence of Ce-containing phases likely contributed to the suppression of excessive grain coarsening during warm rolling. Although the strengthening contribution of these phases was not quantified directly in the present section, the relatively refined microstructure maintained under the 200 °C conditions suggests that rare-earth-containing particles may have played a role in restricting boundary migration and stabilizing the deformation substructure.

3.3 Relationship between Microstructure and Mechanical Properties

The results presented above indicate that the rolling process parameters affected mechanical properties primarily through their influence on microstructural evolution. At low rolling temperature, the stored deformation energy remained high, and recovery was strongly inhibited. Consequently, the alloy developed a finer deformed grain structure, lower recrystallization fraction, and higher dislocation density, all of which contributed to the enhancement of strength and hardness. However, these same features also reduced plastic compatibility during tensile deformation, resulting in lower elongation.

At high rolling temperature, by contrast, thermally activated recovery and recrystallization reduced the internal defect density and facilitated strain accommodation. This microstructural state was beneficial to ductility but weakened the strengthening effect. Therefore, the process-microstructure-property relationship observed in this study can be summarized as follows: increasing reduction ratio intensified deformation strengthening and grain refinement, whereas increasing temperature promoted structural relaxation and recrystallization. The competition between these mechanisms ultimately determined the balance between strength and ductility.

Among all investigated conditions, warm rolling at 200 °C produced the most balanced microstructural state. The alloy retained sufficient deformation substructure to maintain relatively high strength, while partial recrystallization improved the continuity and compatibility of plastic deformation. This finding is consistent with the mechanical results and supports the idea that a moderate rolling temperature can provide a better compromise between strengthening and ductility than either cold rolling or hot rolling alone.

3.4 Prediction of Mechanical Properties Based on Rolling Parameters

To quantitatively evaluate the influence of rolling parameters on mechanical performance, predictive models were established based on the experimental dataset. The model performance for ultimate tensile strength is summarized in Table 2. The quadratic regression model yielded an R^2 value of 0.947, indicating that the major trends in the data could already be captured by a second-order process-property relationship. The random forest regression model further improved the prediction accuracy, achieving an R^2 of 0.981, together with lower RMSE and MAE values.

Table 2 Performance of Predictive Models for Ultimate Tensile Strength

Model	Target property	R²	RMSE (MPa)	MAE (MPa)

Model	Target property	R^2	RMSE (MPa)	MAE (MPa)
Quadratic regression	UTS	0.947	6.8	5.7
Random forest regression	UTS	0.981	3.4	2.8

The comparison between experimental and predicted UTS values is presented in Figure 6. Most data points are distributed closely around the diagonal line, indicating good predictive consistency. The small deviation between prediction and experiment demonstrates that rolling temperature and reduction ratio, together with selected microstructural descriptors, are sufficient to describe the major variation in tensile strength within the investigated parameter range.

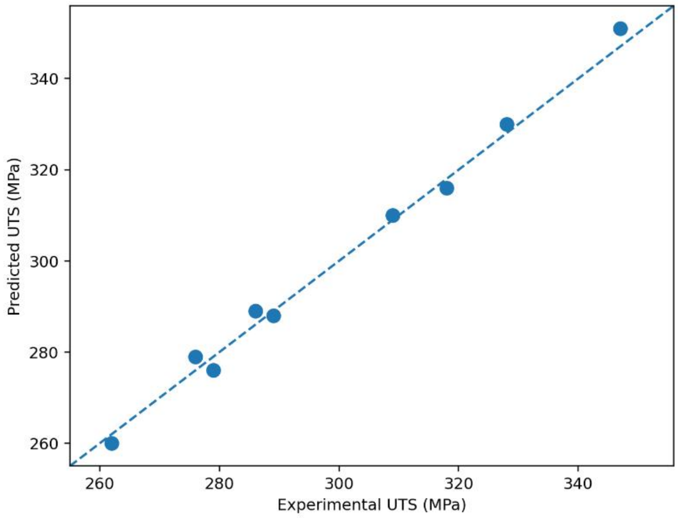

Figure 6 Comparison between Experimental and Predicted Ultimate Tensile Strength

From the modeling perspective, the results suggest that rolling temperature and total reduction ratio were the dominant process variables controlling mechanical behavior, while grain size and recrystallization fraction served as important intermediate descriptors linking process conditions to property response. The improved performance of the random forest model also indicates that the process-property relationship was partially nonlinear. This is reasonable because deformation strengthening, recovery, recrystallization, and grain refinement are coupled phenomena rather than independent linear factors.

Taken together, the predictive analysis confirms that the mechanical performance of rare-earth-containing aluminum alloys can be effectively described by an integrated process-microstructure-property framework. Such a framework provides a useful basis for optimizing rolling schedules and reducing trial-and-error experimentation in future process design.

4 CONCLUSION

This study systematically investigated the effects of rolling temperature and total reduction ratio on the mechanical properties of a rare-earth-containing Al-Mg-Si alloy and established a predictive relationship between processing parameters and mechanical response. Increasing the reduction ratio enhanced the strength and hardness of the alloy but reduced elongation, whereas increasing the rolling temperature weakened the strengthening effect and improved ductility. The highest strength was achieved at 25 °C and 70% reduction, while the best elongation was obtained at 400 °C and 30% reduction. A favorable strength–ductility balance was obtained at 200 °C and 50% reduction.

The observed property variations were closely associated with microstructural evolution during rolling. Low-temperature rolling promoted deformation accumulation, grain subdivision, and work hardening, whereas high-temperature rolling facilitated recovery and recrystallization. As a result, the mechanical properties were governed by the competition between deformation strengthening and recrystallization softening.

In addition, quadratic regression and random forest models were developed, and the random forest model exhibited superior prediction accuracy. This work provides a useful process–microstructure–property framework for rare-earth-containing aluminum alloys. Future work should further consider texture, precipitate evolution, and broader processing conditions to improve mechanistic understanding and enhance the predictive capability of data-driven models.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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