Effect of temperature and strain rate fluctuation on forming limit curve of 5083 Al-Mg alloy sheet

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Abstract
The temperature and strain rate have significant effect on the formability of Al-Mg alloy sheet during warm forming process. Forming limit curve (FLC) is widely used for predicting sheet failure in warm forming simulation. However, the current simulation and optimization may lead to non-robust results, due to not considering the variation of FLC caused by the randomness of sheet temperature and deformation velocity, etc. In this study, a theoretical approach is developed to predict the temperature and strain rate dependent FLC. Backofen constitutive equation is extended, in which the material parameters are fitted as a function of temperature and strain rate by response surface method (RSM). Based on the M-K theory and Logan-Hosford yield criterion, the FLCs of 5083 Al-Mg sheet under different temperature and strain rate conditions are predicted and compared with the experimental results. By integrating the theoretical approach and Monte-Carlo simulation, the temperature and strain rate uncertainties are involved in FLC prediction to reflect manufacturing reality. The upper and lower margins of the FLC variation band are established, which covers the dispersion of the limit strains propagate from temperature and strain rate fluctuation. It is shown that under the combination of a higher temperature and a lower strain rate, the FLC of 5083 Al-Mg sheet is quite sensitive to small fluctuation of temperature or strain rate. In a particular temperature range (413 K–453 K), the FLC of 5083 Al-Mg alloy sheet becomes less sensitive to the fluctuation of temperature or strain rate. All these findings will advance the understanding of the design quality and robustness of the warm forming process.

Keywords
Forming limit curve, warm forming, strain rate, 5083 Al-Mg alloy sheet, uncertainties, statistical analysis

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Introduction
Owing to the excellent high-strength to weight ratio, corrosion resistance, and weight saving potential, aluminum alloys are widely desirable for the automotive and aerospace industry. However, the low formability of aluminum alloy sheets at room temperature limits their use in some products with complex shapes, such as automotive body parts and chassis structures.¹,² With warm forming methods, namely at elevated forming temperature, the formability of aluminum alloys can be greatly improved.³,⁴

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Under warm forming conditions, it is observed that temperature and strain rate affect the material mechanical behaviors significantly. Li and Ghosh\(^5\) demonstrated that the total elongation of Al5182 and Al5754 sheet was greatly enhanced at elevated temperatures and low strain rates. Increasing the strain rate at these temperatures remarkably decreases the total elongation. Mahabunphachai and Koç\(^6\) conducted uniaxial versus biaxial hydraulic bulge loading test of Al5052 and Al6061. They found similar effects of temperature and forming speed. Chen et al.\(^7\) conducted uniaxial and biaxial hydraulic bulge loading test of Al5052 and Al6061. They found similar effects of temperature versus biaxial hydraulic bulge loading test of Al5052 and Al6061. They found similar effects of temperature and strain rate on the ductility of aluminum alloy (AA2024-T351) at strain rates of \(10^{-4} \text{s}^{-1} \sim 9400 \text{s}^{-1}\) with temperatures of 20°C–270°C. Work hardening rates decrease nonlinearly with increases of strain, and significant thermal softening was observed from stress–strain curves. Pandya et al.\(^8\) conducted comprehensive experiments at temperatures ranging from 180°C to 480°C and strain rates ranging from 0.001 to 2/s, in which stress states ranging from simple shear to biaxial tension. They found a negative strain rate effect and a non-monotonic effect of temperature on the ductility of aluminum alloy (AA7075-W). The effects of temperature and strain rate on the formability of aluminum alloy sheet need to be taken into account in warm forming process.

Forming limit curve (FLC) has been widely used as the failure criterion in forming process of aluminum alloy sheet. Based on M-K theory, Abedrabbo et al.\(^9,10\) calculated the FLC of aluminum alloy sheet at different temperatures. The anisotropy coefficients and flow stress equation parameters were fitted as a function of temperature. The calculation results matched the experiment well, but the effect of strain rate was not considered. Toros and Ozturk\(^11\) modified the Nadai model to incorporate strain rate effect. A logarithmic strain rate term was added in the Nadai model, and the rate sensitivity index was eliminated. The flow stress results given by the new model shows acceptable agreement with experimental results. However, the effect of strain rate on FLC was not investigated in his work. By adopting a strain rate-sensitive term to Voce model, Jain\(^12\) calculated the FLC of AA3003 aluminum alloy sheet at elevated temperatures using M-K theory and Barlat YLD2000 yield criterion. It was found that the M-K model is able to capture the temperature dependent formability when the forming temperature increased from RT to 250°C. However, the effect of punch speed is not captured as well due to the limitation of the modified Voce model. Heidari et al.\(^13\) investigated the FLC of 6063 aluminum alloy sheets using numerical and experimental methods at increased temperatures. In their study, the Ayada ductile fracture criterion and the second derivative of the large strain criterion were used to determine necking time and the corresponding forming limit strain.

In reality, the temperature and strain rate always vary in the forming process. Firstly, it’s hard to keep a constant temperature in different regions of a stamping part. Secondly, the strain rate in different spatial locations may differ a lot, especially when forming a part with complex geometry features. Furthermore, material properties also vary from batch to batch due to variation in its manufacturing process. These uncertainties will affect forming limit of sheet metals significantly, and a single forming limit curve could not be an exact description of the formability. Several researchers\(^14\) proposed a more general concept, namely, the forming limit band (FLB) covering the entire dispersion of the limit strain. Banabic and Vos\(^15\) developed a theoretical approach to predict the two margins of the limit band, where the variation of material properties was taken into account. Bayat et al.\(^16\) developed a statistical approach to generate FLB of boron steel (22MnB5), by incorporating the effect of material scatter as well as the numerical parameters. In this way, the necking of material is not represented by a single forming limit curve, but by a band of forming limit curves.

In general, the FLC is a good measure of failure caused by localized necking. However, under some particular process, for example hemming, hole expansion/flanging,\(^17,18\) Origami-based sheet metal (OSM) bending,\(^19\) stretch-bending with small die radii,\(^20\) incremental forming\(^21\) etc., various failure types can occur, such as edge crack,\(^17\) bending induced surface crack,\(^22\) shear induced crack,\(^23\) non-symmetric thinning\(^24\) etc. It is often found that the local necking is suppressed and sheet metal can develop stable plastic deformation until fracture. Furthermore, depending on the ductility of the material, for example some aluminum alloys with relatively low formability,\(^25,26\) advanced high strength steels (AHSS) with complex microstructures,\(^27\) fracture may occur without noticeable necking. For 2024-T3 sheets,\(^26\) TWIP steel sheets\(^27\) with low ductility, fracture may occur prior to the localized necking. Other factors such as sheet thickness,\(^28\) grain size,\(^29\) loading history,\(^30\) planar anisotropy,\(^31\) anisotropic hardening,\(^32\) evolving effects of anisotropy\(^33\) etc. also have significant effect on forming limit of sheet metal. The traditional FLC without considering these physical mechanisms, may over or underestimate the actual formability.

Recently, researchers considered fracture forming limit curve (FFLC),\(^34\) extended FLC concept (X-FLC),\(^35\) etc. to define sheet metal forming limit, in order to cover different types of failure mechanisms. The FFLC aim to evaluate the limit strains at the onset of fracture from uniaxial compression to biaxial tension region. By using anisotropic material models and the path independent approaches, Basak and Panda,\(^36,37\) Park et al.\(^38,39\) have demonstrated the potential of the
FFLC in describing sheet metal forming limit over a wide range of stress states. The X-FLC includes the traditional FLC, the FFLC and the bending limit curve (BLC). It can describe various process limits, for example shear induced cracks in parts forming with small die raiii, edge cracks in hole expansion test, bending induced surface cracks in hemming, etc. Depending on the type of material and on the deformation process, the FFLC may lie below or above the FLC, or intersect with the FLC, \(^4\) which suggests complicated underlying failure mechanisms. Oud\(^1\) assessed the formability of AA7075 sheet at elevated temperature by means of Marciniak test. The FLCs and FFLCs for all temperatures approach each other near the equi-biaxial condition, indicating a competition between the local necking and ductile fracture in this region. But for the uniaxial tension and plane strain state, the FFLCs far exceed the FLCs, which indicates local necking may occur before fracture. The interplay between necking and fracture at elevated temperature is still not well understood and needs further research. We have limited ourselves in this paper only to localized necking that limits warm forming process.

As discussed above, temperature and strain rate significantly affect the FLC of aluminum alloy sheet during warm forming. The variation of FLC which caused by temperature and strain rate fluctuation needs to be considered in FE-simulation and process development. Therefore, the current study aims to investigate the effect of temperature and strain rate fluctuation on the FLC of 5083 Al-Mg alloy sheet. In section 2, a theoretical model for predicting temperature and strain rate dependent FLC is established, which can capture failure caused by local necking during warm forming. In section 3, stochastic analysis is performed by integrating the theoretical model and Monte-Carlo simulation, which can predict the FLC variation band caused by the random distribution of temperature and strain rate. Section 4 validate the theoretical model by comparison with the experimental data, and investigate the influence of temperature and strain rate fluctuation on the FLC. In the end, the conclusions are drawn in Section 5.

**Temperature and strain rate dependent FLC modeling**

*Constitutive equation coupling with temperature and strain rate*

In order to describe the stress-strain relationship under different temperature and strain rate conditions, an appropriate constitutive equation is needed. Fields and Backofen proposed a constitutive equation that includes the strain-rate sensitivity:

\[
\bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}) = C^{\text{eff}}\dot{\varepsilon}^m
\]

where \(C\) (strength hardening coefficient), \(n\) (strain hardening exponent) and \(m\) (strain rate sensitivity index) are material parameters. \(\dot{\varepsilon}\) is effective plastic strain and \(\dot{\varepsilon}\) is effective strain rate. \(\sigma\) is effective stress.

Uniaxial tensile tests of 5083 Al-Mg alloy sheet was conducted at a wide range of strain rate and temperature by Naka and Yoshida.\(^3\) Based on the experimental data, the coefficients \(C\) and \(n\) of equation (1) under different temperature and strain rate conditions can be obtained. The strain rate sensitivity index \(m\) is determined by the following equation.

\[
m = \frac{\ln(\sigma_2/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}
\]

Material parameters \(C\), \(n\), and \(m\) are expressed as a function of temperature and strain rate. The constitutive equation becomes:

\[
\bar{\sigma}(\bar{\varepsilon}, \dot{\varepsilon}, T, \dot{\varepsilon}) = C(T, \dot{\varepsilon})\dot{\varepsilon}^m(T, \dot{\varepsilon})\bar{\varepsilon}^n(T, \dot{\varepsilon})
\]

Response surface methodology (RSM) is used to calculate material parameters as a function of temperature and strain rate. A second-order polynomial model is commonly used. In general, the response model can be written as follows:

\[
y(x) = \beta_0 + x^Tb + x^T Bx
\]

where \(\beta_0\), \(b\), \(B\) are coefficients or coefficient matrices for design variables \(x\). \(y(x)\) is the corresponding response value.

Polynomial models in the form of equation (4) are fitted to describe the relationship of material parameters with temperature and strain rate. The regression coefficients are calculated, and the fitted equations for \(n\) and \(m\) are:

\[
n(x_1, x_2) = 0.0082x_1 + 0.3668x_2 - 2.21 \times 10^{-5} x_1^2
\]

\[
+ 0.0098x_2 - 0.0028x_1x_2 + 2.46 \times 10^{-8} x_1^3 + 3.39 \times 10^{-4} x_2^3
\]

\[
+ 6.94 \times 10^{-6} x_1 x_2^2 - 4.15 \times 10^{-2} x_1 x_2^2 - 1.09 \times 10^{-1} x_1^3
\]

\[
- 2.04 \times 10^{-5} x_2^4 - 5.39 \times 10^{-3} x_1 x_2^2 - 9.98 \times 10^{-7} x_1 x_2^3
\]

\[
+ 3.88 \times 10^{-8} x_1 x_2^2 + 0.7722
\]

\[
m(x_1, x_2) = 9.34 \times 10^{-4} x_1 + 0.0203x_2 - 7.12 \times 10^{-5} x_1 x_2
\]

\[
- 2.6 \times 10^{-6} x_1^2 + 4.96 \times 10^{-4} x_2^3 + 2.26 \times 10^{-8} x_1 x_2
\]

\[
+ 3.45 \times 10^{-7} x_1 x_2^2 + 3.08 \times 10^{-9} x_1^3
\]

\[
- 3.9 \times 10^{-5} x_2^2 - 0.1294
\]

where \(x_1\) and \(x_2\) are the coded values of \(T\) and \(\ln \dot{\varepsilon}\).
Significance of the fitted models is judged by analysis of variance. It is indicated that the two models are significant at 95% confidence level. Furthermore, $R^2$ is calculated to check the model adequacy. A high proportion of variability ($R^2 > 0.98$) imply that the two regression models are reliable.

To visualize the combined effect of temperature and strain rate on material parameters, the response surfaces contour plots are generated. As shown in Figure 1, $n$ decreases as the rising of temperature, and increases as the increasing of strain rate. In contrast, $m$ increases with the rising of temperature and decreases with the increasing of strain rate. Generally, the formability of sheet metal increases as $n$-value increases, as well as $m$-value increases. In order to obtain the optimal formability of aluminum alloy sheet, forming temperature and forming speed need to be matched reasonably.

Naka et al.\textsuperscript{43} conducted experiments to determine the yield locus of 5083 Al-Mg alloy sheet at elevated temperatures. It was shown that a higher order yield function, such as Logan-Hosford yield criterion, fitted well with the yield locus of 5083 Al-Mg alloy sheet under different temperature conditions.

Assuming plane stress state and normal anisotropy, Logan-Hosford yield criterion\textsuperscript{44} is represented by the following equation:

$$|\sigma_1|^M + |\sigma_2|^M + r|\sigma_1 - \sigma_2|^M = (1 + r) \sigma^M$$

where $M$ is stress exponent and $r$ the ratio of normal anisotropy. $\sigma_1$ and $\sigma_2$ are principal stresses. $\sigma$ is effective stress. Suggested values of $M = 6$ and $M = 8$ for BCC and FCC materials, respectively, are based on crystallographic calculations.

**FLC prediction**

The widely used instability model for predicting FLC was proposed by Marciniak and Kuczynski.\textsuperscript{45} which is based on the assumption that there exists an imperfection zone, where localized necking occurs. This imperfection may be caused by the geometrical inhomogeneity, where the groove zone has a slightly smaller value of thickness compared with the homogeneous region. The initial thickness non-homogeneity is described as “coefficient of initial non-homogeneity,” $f_0$, which is the ratio of the initial thickness in the groove region B and the uniform region A: $f_0 = t_{B0}/t_{A0}$. This initial groove grows continuously with plastic straining to form eventually a localized neck.

As deformation grows, the strain increment in region B ($\Delta e_{1B}$) develops faster than that in region A ($\Delta e_{1A}$). As the forming process approaches necking, region B should approach the plane strain condition and strain ceases in region A. Region B will then continue to deform until it fails (tearing). This strain state, just outside the neck, is the maximum strain that can be achieved during this process and the strains, $e_{1A}$ and $e_{2A}$ are known as the forming limit strain.

The principle and the fundamental equations of M-K model are described in Shen et al.,\textsuperscript{33} as well as the algorithm that needs to solve the non-linear force equilibrium equation. In this work, if the convergence criterion ($\Delta e_{1B}/\Delta e_{1A} > 10$) is satisfied, the analysis is terminated and the corresponding major and minor strain ($e_{1A}$ and $e_{2A}$) in region A are recorded. If the analysis is repeated for different strain ratios, the forming limit strain for each strain ratio can be determined and plotted in the minor versus major strain diagram.
By connecting these limit strain points, we obtain a curve that indicates the onset of the localized necking, which is known as the FLC.

**Stochastic analysis of FLC**

**Statistical description of process uncertainty**

In manufacturing reality, the process uncertainties such as the fluctuation of the temperature field and the deformation velocity field in a stamping part always exist, as shown in Figure 2. In this study, temperature and strain rate variables are assumed to be a Gaussian type distribution. The range and standard deviation (SD) of the temperature and strain rate for each mean value are listed in Table 1.

The temperature fluctuation range is assumed to be $\pm 10K$ around the mean value, representing the temperature field fluctuation at different spatial locations of a stamping part. The strain rate fluctuation range is assumed to be $\pm 50\%$ around the mean value, considering the deformation velocity may vary a lot in different spatial locations of a stamping part, especially when forming a part with complex geometry features.

**Stochastic analysis**

Monte-Carlo simulation (MCS) has been widely used for stochastic analysis, in order to predict the influence of input parameters (e.g. control and noise factors) variation on the final product manufacturing quality. For predicting the mean and variance, it is probably the best-known method. However, performing MCS based stochastic analysis usually requires a large number of experiments (more than 100 for reliable results), it is unpractical and too costly to apply directly in manufacturing practices.

In order to take full advantage of MCS, and to apply it cost effectively, an integrated stochastic analysis method is developed. The MCS is used to generate a
A series of random inputs, namely the combinations of temperature and strain rate, according to their statistical descriptions shown in Table 1, which reflect the fluctuation of process factors in warm forming reality. The theoretical FLC model is used to predicted the response (forming limit strains) from each set of the random inputs, and plotted in the minor versus major strain diagram as scatter points around the FLC predicted with the nominal value shown in Table 1. Then, the upper and lower margins (FLC variation bands) can be established, which covers these limit strains scattering range. The principle of stochastic analysis of FLC is shown in Figure 2, and the main steps are explained below:

**Step 1: Generate a set of random inputs based on MCS.** According to the statistics listed in Table 1, a sequence of random inputs \( x_{1i} \) and \( x_{2i} \) conformed to their statistical distribution can be generated.

**Step 2: Predict the forming limit strains based on the theoretical model.** \( y = f (x_{1i}, x_{2i}) \). The theoretical FLC model is applied, where \( y \) represents forming limit strains, \( x_{1i} \) and \( x_{2i} \) represent the random inputs of temperature and strain rate respectively.

**Step 3: Evaluate the response and analyze the results.** Record the predicted limit strain results as \( y_i \) and repeat steps 1 and 2 for \( i = 1 \) to \( n \). The scattering limit strains \( y_i \) are plotted, and the FLC variation bands can be established. The width of the upper and lower band indicates the stability of process limit.

By integrating MCS and the theoretical model, the stochastic analysis can be performed cost-effectively to determine how randomness of the input process parameters (e.g. temperature and strain rate fluctuation) affects the final FLC results.

### Results and discussion

**Validation of the FLC model**

The predicted FLC results are compared with the experimental results. By performing punch stretch-forming tests of 5083 Al-Mg alloy sheet, Naka et al.\(^46\) determined the forming limit strains at elevated temperature from 293 K to 573 K over a wide range of strain rates (5.56 \( \times 10^{-5}/s \)–5.56 \( \times 10^{-2}/s \)). The experimental data are shown in Figure 3. The predicted FLC results are also illustrated in Figure 3.

The \( f_0 \)-value in M-K model and the \( M \)-value in yield criterion are chosen in order to obtain a good agreement with experimental data. For strain rate 5.56 \( \times 10^{-5}/s \), the best agreement between the predicted results and experiment results is observed when \( f_0 \) equals to 0.99, \( M \) equals to 6 for 573 K and 423 K, and 8 for 293 K and 353 K. For strain rate 5.56 \( \times 10^{-3}/s \), \( f_0 \) is 0.96, \( M \) is 2 at different temperature. For strain rate 5.56 \( \times 10^{-2}/s \), the \( f_0 \) and \( M \) are fixed to 0.93 and 2, respectively.

As shown in Figure 3, under three different strain rate conditions, the predicted FLC rise monotonically as temperature increases, which shows the same trend with experimental data. Under lower strain rate condition, as shown in Figure 3(a), the predicted FLC rise significantly as temperature increases. Under higher strain rate condition, as shown in Figure 3(b) and (c), the predicted FLC becomes less sensitive to temperature. It is demonstrated that the predicted FLC results are in good agreement with the experimental data under different temperature and strain rate conditions. The established theoretical model is able to predict temperature and strain rate dependent FLC of 5083 Al-Mg sheet with enough accuracy and convenience.

**Effect of temperature and strain rate fluctuation**

As shown in Table 1, MCS is run 500 times for each temperature level with a fixed strain rate of 5.56 \( \times 10^{-5}/s \). The forming limit band (FLB) with an upper and a lower margin which covers the dispersion of the limit strains are illustrated in Figure 4(a). The FLC predicted at each mean value, namely the base line, are also plotted in Figure 4(a). Similarly, MCS is run 500 times for each strain rate level with a fixed temperature of 573 K. The FLB and the corresponding base line are illustrated in Figure 4(b).

As shown in Figure 4(a), the base lines rise monotonically as temperature increases, indicating that the formability is enhanced at elevated temperature. In this
case, the base lines lie just in the center of the corresponding variation bands. As temperature increases, at first the FLB become narrower from 353 K to 453 K, and then become wider from 453 K to 553 K. It's observed that the formability at elevated temperature can become quite unstable due to small fluctuation of temperature. For example, the width of FLB reaches the maximum value at 553 K. It is also found that at

![Figure 3.](image1.png)

**Figure 3.** Comparison of the predicted FLC with experimental data: (a) strain rate $5.56 \times 10^{-5}/s$, (b) strain rate $5.56 \times 10^{-3}/s$, and (c) strain rate $5.56 \times 10^{-2}/s$.

![Figure 4.](image2.png)

**Figure 4.** The base line and the FLC variation band caused by (a) temperature fluctuation and (b) strain rate fluctuation.
453 K, the FLC is less sensitive to the fluctuation of temperature (the width of FLB reaches the minimum value at 453 K), while the FLC is greatly enhanced compared to that at room temperature (see Figure 3).

As shown in Figure 4(b), the base lines rise monotonically as strain rate decreases, indicating that the formability can be enhanced at a lower deformation velocity. It is found that the base lines are close to the lower variation bands in this case, suggesting that the statistic distributions of the limit strains are not Gaussian type. As strain rate decreases, the FLB become wider, and the width of FLB reaches the maximum value at a lower strain rate of $5.56 \times 10^{-2}/s$.

It is observed that at a lower strain rate and a higher forming temperature (573 K), the FLC can be greatly enhanced, but it may become unstable due to the fluctuation of temperature and strain rate.

The width of FLB represents the dispersion range of the limit strains, which indicates the stability of process limit. In our analysis, it is found that for a given temperature and strain rate combination, the different strain states, for example, uniaxial tension, plane strain and equal biaxial stretching etc., have a small impact on the width of FLB. This might because under a given temperature and strain rate condition, the $f_r$-value in M-K model and the $M$-value in yield criterion remain the same in the stochastic analysis. Therefore, the vertical distance between the upper and lower variation band under the plane strain state is used to determine the width of FLB.

In order to further explore the effect of temperature and strain rate fluctuation, more temperature and strain rate levels are adopted. Temperature is extended to 11 levels; varying from 353 K to 553 K with interval of 20 K. Temperature variation range is still ± 10K around its mean value. Strain rate variation range is ± 50% around the mean value of $5.56 \times 10^{-2}/s$, $5.56 \times 10^{-3}/s$, $5.56 \times 10^{-4}/s$, $5.56 \times 10^{-5}/s$.

The effect of temperature fluctuation on the width of FLB is shown in Figure 5(a). For all strain rate levels, the width of FLB firstly decreases monotonically and reaches the minimum value at 413 K–453 K, then continue increases monotonically and reaches the maximum value at 553 K. From 413 K to 453 K, the FLC of 5083 Al-Mg sheet is less sensitive to the fluctuation of temperature and strain rate.

The influence of strain rate fluctuation on the width of FLB is shown in Figure 5(b). For all temperature levels, the width of FLB decreases monotonically as strain rate increases, and reaches the minimum value at the highest strain rate ($5.56 \times 10^{-2}/s$). Under the combination of a higher temperature and a lower strain rate, the width of FLB reaches the maximum value. In this case, the FLC of 5083 Al-Mg sheet is quite sensitive to the fluctuation of temperature or strain rate.

It is observed that in a particular temperature range (413 K–453 K), the FLC of 5083 Al-Mg sheet becomes insensitive to the fluctuation of temperature. For other aluminum alloy series, similar phenomenon is also reported in literature. Abedrabbo et al. calculated the FLC of AA3003-H111 and AA5182-O aluminum alloy sheet at elevated temperature. The predicted FLC becomes insensitive to temperature in the range of 177 K–204 K. For AA5083 at 150°C–300°C, the predicted FLC shows small difference at 150°C–240°C, which is close to the temperature range (413 K–453 K) reported in this study. Beyond this temperature range,
range, the predicted FLC at 300°C is much higher than those at 150°C and 240°C.

Conclusions

- A theoretical approach is developed to predict the FLC of 5083 Al-Mg alloy sheet under different temperature and strain rate. The predicted FLC results are in good agreement with the experimental data under different temperature and strain rate conditions.
- By integrating the theoretical approach and Monte-Carlo simulation, stochastic analysis is performed to predict the FLB caused by the fluctuation of temperature and strain rate, which are assumed to be a Gaussian type distribution.
- Under the combination of a higher temperature and a lower strain rate, the FLC of 5083 Al-Mg sheet is quite sensitive to small fluctuation of temperature or strain rate. In a particular temperature range (413 K–453 K), the FLC of 5083 Al-Mg alloy sheet becomes less sensitive to the fluctuation of temperature or strain rate.

The insight obtained in this paper will help to understand the design quality and robustness of the warm forming process.

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Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

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