

Prediction of limit drawing ratio in deep drawing process of Mg alloy AZ31 using Fuzzy Logic

*Predicción de la relación límite de embutición en el conformado mecánico
por embutido de la aleación de Mg AZ31 usando Lógica Fuzzy*

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ABSTRACT

The interest in magnesium alloys has progressively increased in several industrial fields in recent years, and AZ31 has become an object of the study of lightweight development. Due to its low density and high specific strength, magnesium alloys represent a promising alternative to aluminum alloys and high strength steels, especially for applications in the automobile industry, being used in structural components to reduce weight and, consequently, improve performance fuel efficiency. In recent decades, several tests were conducted to evaluate the formability of AZ31 and showed its high dependency on the temperature range. The main objective of the present study is to propose a fuzzy model to predict the limit drawing ratio (LDR) of an AZ31 sheet by varying its thickness, temperature, and speed in wide ranges. In order to validate the proposed model, comparisons were made with 6 studies performed by other authors –an amount of 46 experimental tests–, showing a very good agreement between experimental results and fuzzy results. The model predicts the limit drawing ratio with an accuracy of 92.1%.

Keywords: Lightweight alloy, deep drawing, sheet metal forming, Fuzzy logic, limit drawing ratio.

RESUMEN

El interés por las aleaciones de magnesio ha aumentado progresivamente en varios campos industriales en los últimos años y el AZ31 se ha evolucionado hacia el desarrollo de aleaciones no ferrosas de bajo peso. Debido a su baja densidad y alta resistencia específica, las aleaciones de magnesio representan una alternativa prometedora a las aleaciones de aluminio y a los aceros de alta resistencia, especialmente para aplicaciones en la industria automovilística, utilizándose en componentes estructurales para reducir el peso y, en consecuencia, mejorar la eficiencia del combustible. En las últimas décadas, se han realizado varias pruebas para evaluar la formabilidad del AZ31 y se ha demostrado su alta dependencia del rango de temperaturas. El principal objetivo del presente estudio es proponer un modelo fuzzy para predecir el relación límite de embutición (RLE) de una lámina de AZ31 variando su espesor, temperatura y velocidad en amplios rangos. Para validar el modelo propuesto, se hicieron comparaciones con 6 estudios realizados por otros autores –una cantidad de 46 pruebas experimentales–, mostrando una muy buena concordancia entre los resultados experimentales y los resultados fuzzy. El modelo predice el relación límite de embutición con una precisión del 92,1%.

Palabras clave: Aleación ligera, embutición profunda, formabilidad de chapa, Lógica Fuzzy, relación de embutición límite.

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INTRODUCTION

Deep drawing is a sheet metal forming process widely used in several industrial fields, such as automotive, aerospace, and manufacturing [1, 2]. As the general vehicle industry aims to increase fuel efficiency, reducing structural weight by using lightweight materials is one of the possibilities to reach this achievement [3, 4]. As the lightest structural alloys, magnesium alloys represent a promising alternative with many advantages compared with steel and aluminum alloys [3, 5-9]. Nevertheless, due to its hexagonal closed-packed (HCP) crystal structure, magnesium alloys show poor formability at room temperatures, being difficult to be deformed and shaped [1-24]. However, excellent ductility can be obtained by increasing the temperature and other conditions, such as drawing speed [12, 25].

To overcome these issues, several researchers conducted experimental tests to optimize parameters to achieve better formability results. Experiments with AZ31, a magnesium alloy -3% Mg, 1% Zn- [26] were conducted under different circumstances, in wide ranges. In this study, the experimental tests used to create a database covered the following parameters: thickness: 0.5 mm to 1.3 mm; temperature: 20 °C to 300 °C; and drawing speed: 0.5 mm/s to 100 mm/s.

In order to reduce the stamping process steps, it is important to achieve the most significant limit drawing ratio (LDR), which can be defined essentially as the highest value of the ratio of the blank diameter to punch diameter which can be drawn out successfully (without failure) [27].

As Fuzzy logic has shown to be a simple method to predict outputs in other manufacturing process with good accuracy, such as laser assisted turning [28]. The present work uses fuzzy modeling to predict the limit drawing ratio in a deep drawing process of AZ31 magnesium alloy. Experiments carried out by researchers [13-18] were used to create a knowledge database for the fuzzy modeling. The Gaussian membership function is assumed for defining input variables and output parameters. Fuzzy rules are defined by using experimental observations of the authors. The proposed model can predict a limit drawing ratio for a wide range of process parameters with a predictor error of only 7.9%.

LIMIT DRAWING RATIO EVALUATION

In order to develop a model to predict the LDR, three fundamental parameters were selected to measure the deep drawability of the AZ31 sheet metal: blank thickness, punch speed, and work temperature. The parameters and their respective roles are described as follows.

Blank thickness

The blank material thickness influences the LDR by affecting the tendency to wrinkling, pressure on the die, and deformation forces. In deep drawing, die pressure increases proportionally to the square of the blank thickness; therefore, thick sheets present less tendencies to wrinkle than thin ones [29, 30]. Besides, the increase of blank thickness postpones the failure [29]. Despite thinning in the deep drawing being an undesirable effect, it is also unavoidable, and the uniformity of the blank affects the strain localization since thickness reduction occurs [9].

Punch speed

Magnesium alloys are known to have a higher strain rate sensitivity [4, 6, 31]. The formation of small cracks near the punch radius region of the cup piece was observed as the punch velocity increased [4]. In contrast, drawabilities improvements have been reported by reducing the punch velocity [12]. Particularly for AZ31 alloy, the increase of punch velocity showed a decrease in drawing performance [32].

Work temperature

Several researchers highlighted that the deep drawing process of Mg alloys is strongly influenced by the temperature range [4, 33-35]. Due to their HCP structure, these alloys have a limited number of plastic deformation modes available and therefore reported poor formability at room temperature [24, 33, 36, 37]. By contrast, tests performed under elevated temperatures showed improvements in formability because of the activation of the non-basal slip system [38, 39]. However, when the temperature exceeded 350 °C, sections of cracks were formed. Besides being associated with the composition of the alloy itself, this event is also related to the contractions caused by regional heating and (unintended) cooling [32].

FUZZY LOGIC MODELLING

Professor Lotfi Zadeh developed the Fuzzy logic known nowadays. He noted that Boolean logic was not sufficient to model industrial, chemical or biological activities [40]. Currently, Fuzzy logic is considered a technique of excellence in the area of process control due to its ability to “classify“ inputs and outputs in more than one characteristic, using parameterization through ranges and membership functions. Due to the mutual influence of input data, predicting output data is a complex task. Therefore, the present work uses Fuzzy logic to predict the LDR (Limit Drawing Ratio) in the process of deep drawing an AZ31 sheet, starting from the values

of thickness, temperature, and speed of the punch. Figure 1 presents a scheme of Fuzzy modeling.

Through bibliographic studies, ranges were assumed for input and output parameters according to the Fuzzy logic and are exposed in Table 1. The Gaussian membership function was considered for all input and output parameters under study, as shown in Figure 2 and Figure 3. The steps involved in fuzzy modeling are the follows:

1. Assumption of ranges and membership functions for input and output parameters;
2. Definition of rules based on the experiments results and knowledge base;
3. Defuzzification.

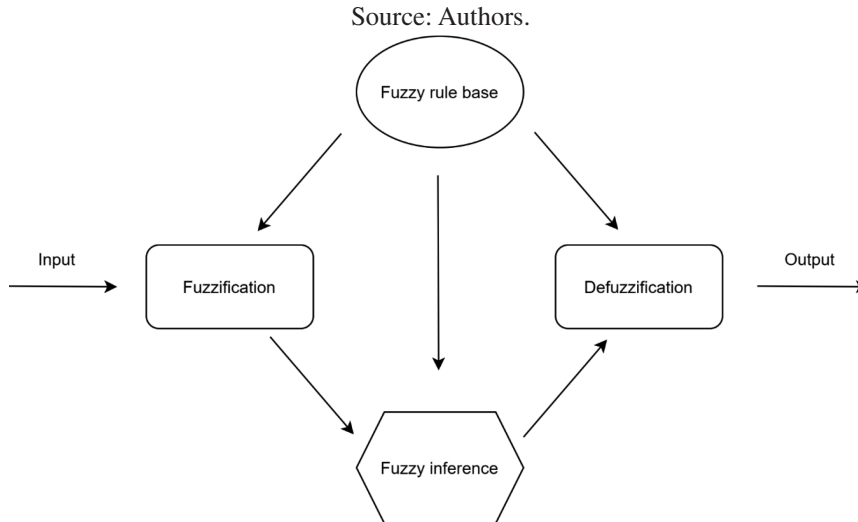


Figure 1. Scheme of Fuzzy modelling.

Table 1. Assumption of ranges of input and output parameters in fuzzy modeling.

| Input | Range | | | | | |
|------------------|------------------|----------|------------|------------|----------|----------|
| Thickness (mm) | Thin | | Regular | | Large | |
| | 0.1-0.8 | | 0.6-1.5 | | 1.3-3.5 | |
| Velocity (mm/s) | Too slow | Slow | Preferable | Fast | Faster | Too fast |
| | 0.1-0.7 | 0.5-3.0 | 2.0-30 | 20-50 | 30-80 | 60-100 |
| Temperature (°C) | Room temperature | Warm | Transition | Preferable | Too high | |
| | 20-50 | 40-100 | 80-160 | 120-290 | 250-400 | |
| Output | Range | | | | | |
| LDR | Very low | Low | Good | Better | Great | |
| | 1-1.5 | 1.35-2.0 | 1.8-2.5 | 2.25-2.7 | 2.4-3.2 | |

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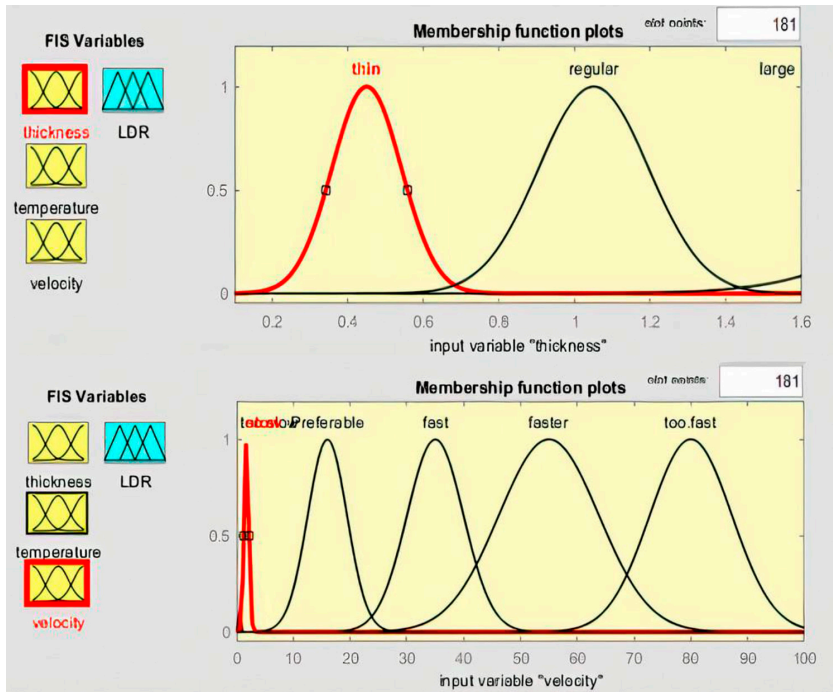


Figure 2. Assumption of inputs thickness and velocity parameters as gaussian functions.

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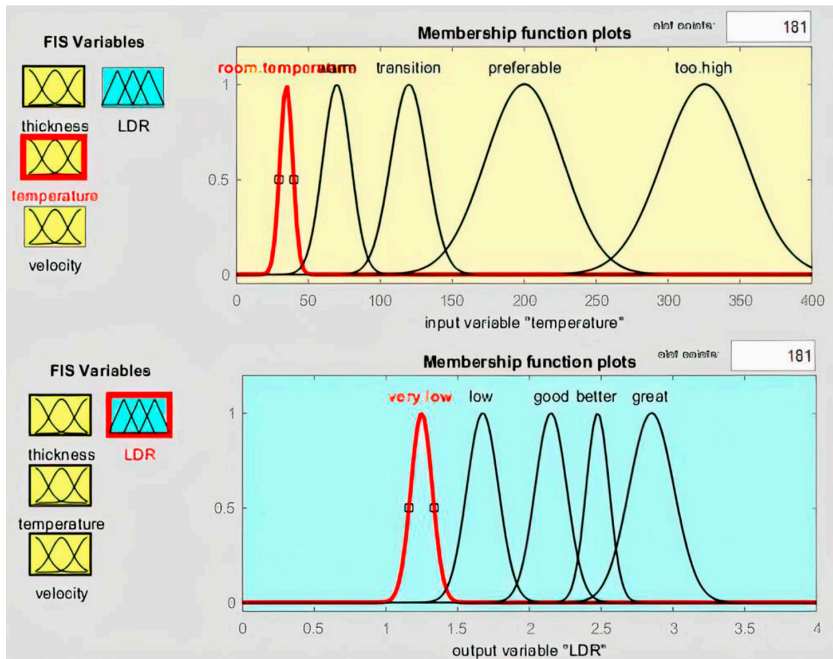


Figure 3. Assumption of input temperature and output LDR parameters as gaussian functions.

Fuzzy rules

If and then rules are given as input to the inference engine for fuzzy modeling of deep drawing of the magnesium alloy AZ31. Rules were created based on the experimental studies of limit drawing ratio performed by other authors [13-18] and are disposed of in Table 2.

RESULTS AND DISCUSSION

The authors [13-18] performed deep drawing experiments on AZ31 using different thickness ranges, velocities, and temperatures. The present study aimed to develop a fuzzy model that congregates wide ranges. The model was validated with the authors’ respective experimental results. Table 3 and Figure 4 - Figure 12 depict the comparison between fuzzy modeling and 46 results measured experimentally. The prediction error is calculated by using the difference between experimental results and fuzzy model results to experimental results. The model reached an average prediction error of 7.9%.

In Figure 4 - Figure 12, LDR experimental results obtained by other authors [13-18] and fuzzy results

obtained by the present study are represented. Figure 4 shows a noticeable increase in the LDR when the working temperature is above 150 °C. This phenomenon results from the thermal activation of pyramid sliding planes in the hexagonal closed-packed structure [13]. Moreover, the Fuzzy model represented experimental results with an average precision of 94.58%. The lower accuracy point occurred in T = 100 °C, performing a precision of 83.04%.

Figure 5 shows the results of deep drawing tests [16], in which LDR was evaluated using a range from room temperature (RT) to 240 °C. It is markable the difference between lower and higher temperatures, as at RT, the LDR reaches 1.3, and at T = 200 °C, it reaches 2.65. Besides, it is inferable that a range between 50 °C and 90 °C is the minimum to ensure good deep drawability. It is also noticeable that the LDR decreased at T = 240 °C; this phenomenon occurs because, above 200 °C, the strain hardening exponent of a magnesium alloy decreases due to the reducing amount of twinning. Regarding prediction, the Fuzzy model achieved an average precision of 91.34%, with the lower point of accuracy in T = 240 °C, reaching 87.73% of precision.

Table 2. Fuzzy rules.

| Rule (n°) | IF | | | Then |
|-----------|-----------|------------------|------------|----------|
| | Thickness | Temperature | Velocity | LDR |
| | thin | transition | slow | very low |
| 2 | regular | room temperature | preferable | very low |
| 3 | thin | room temperature | too slow | very low |
| 4 | regular | warm | preferable | low |
| 5 | regular | warm | slow | low |
| 6 | thin | transition | fast | good |
| 7 | regular | preferable | too fast | good |
| 8 | large | too high | too slow | good |
| 9 | regular | too high | preferable | good |
| 10 | regular | transition | preferable | good |
| 11 | thin | preferable | slow | good |
| 12 | large | preferable | fast | better |
| 13 | regular | preferable | faster | better |
| 14 | regular | preferable | too slow | better |
| 15 | thin | preferable | slow | better |
| 16 | regular | preferable | preferable | better |
| 17 | thin | preferable | fast | great |

Source: Authors.

Table 3. Limit drawing ratio results.

| Experiment | Fuzzy model | Prediction error (%) | Experiment | Fuzzy model | Prediction error (%) |
|------------|-------------|----------------------|------------|-------------|----------------------|
| 1.30 | 1.25 | 3.84% | 2.25 | 2.25 | 0.00% |
| 1.48 | 1.59 | 7.43% | 2.30 | 2.26 | 1.74% |
| 1.48 | 1.66 | 12.16% | 2.30 | 2.26 | 1.74% |
| 1.49 | 1.54 | 3.35% | 2.31 | 2.26 | 2.16% |
| 1.50 | 1.80 | 20.00% | 2.33 | 2.15 | 7.72% |
| 1.55 | 1.92 | 23.87% | 2.34 | 2.38 | 1.70% |
| 1.64 | 1.73 | 5.49% | 2.36 | 2.17 | 8.05% |
| 1.65 | 1.93 | 16.96% | 2.38 | 2.26 | 5.04% |
| 1.65 | 1.98 | 20.00% | 2.41 | 2.43 | 0.83% |
| 1.65 | 1.89 | 14.54% | 2.44 | 2.47 | 1.23% |
| 1.83 | 2.14 | 16.93% | 2.44 | 2.24 | 8.19% |
| 1.83 | 1.89 | 3.27% | 2.47 | 2.47 | 0.00% |
| 2.00 | 2.14 | 7.00% | 2.50 | 2.50 | 0.00% |
| 2.00 | 1.89 | 5.50% | 2.51 | 2.25 | 10.35% |
| 2.00 | 2.29 | 14.50% | 2.52 | 2.47 | 1.98% |
| 2.14 | 2.14 | 0.00% | 2.52 | 2.47 | 1.98% |
| 2.14 | 2.03 | 5.14% | 2.52 | 2.47 | 1.98% |
| 2.18 | 2.46 | 11.38% | 2.56 | 2.26 | 11.72% |
| 2.20 | 2.47 | 12.27% | 2.63 | 2.26 | 14.06% |
| 2.22 | 2.15 | 3.15% | 2.65 | 2.47 | 6.79% |
| 2.22 | 2.17 | 2.25% | 3.00 | 2.20 | 26.67% |
| 2.25 | 2.15 | 4.44% | 1.48 | 1.92 | 29.70% |
| 2.25 | 2.26 | 0.44% | 2.50 | 2.26 | 6.40% |

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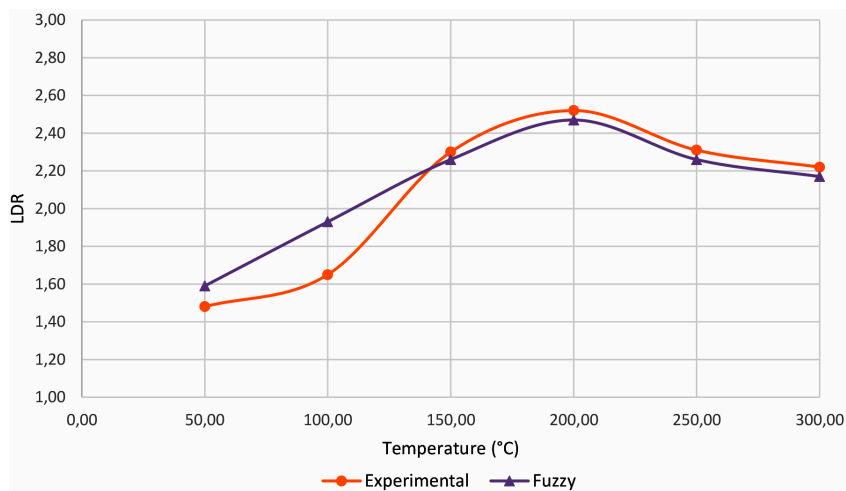


Figure 4. Variant temperature - Thickness: 1mm and Velocity: 5mm/s.

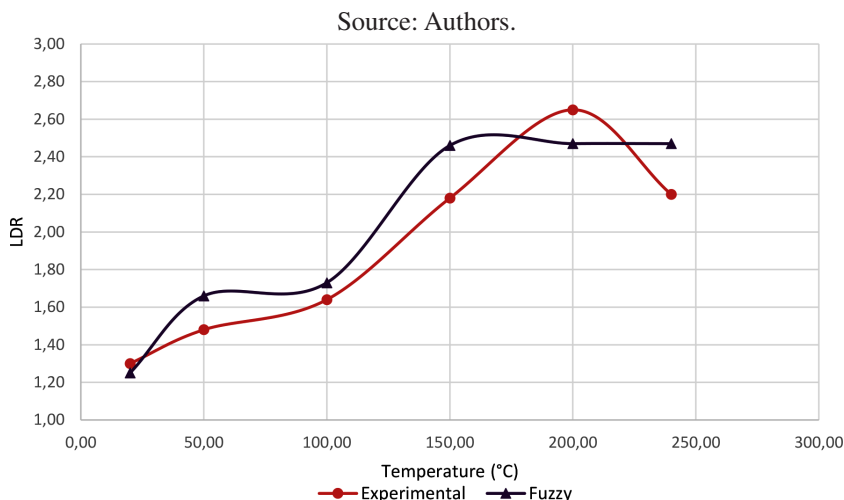


Figure 5. Variant temperature - Thickness: 0.8 mm and Velocity: 0.5 mm/s.

Figure 6 represents an experiment [17] in which a temperature range between 105 °C and 170 °C was selected. As expected, it is observed that LDR improves when the working temperature is increased since magnesium possesses poor formability at lower temperatures due to its HCP structure. Besides, it is evident that at T = 170 °C, an LDR greater than 2.4 is achieved. The average precision achieved by the Fuzzy model was 89.58%, and the lower accuracy point occurred in T = 105 °C, with 80% of precision.

becomes evident that LDR decreases as forming velocity increases at the same temperature. Due to this, it is inferable that such behavior at higher speeds occurs because of the overhardening on the flange, which increases the deformation resistance and, reduces LDR. Furthermore, the Fuzzy model obtained an average precision of 90.31%, whereas the lower accuracy point was also T = 105 °C, with 80% precision.

By comparing Figures 6 and Figure 7, both represent conducted experiments in the same study [17], it

Figure 8, it is possible to infer that increasing velocity leads to lower LDR due to higher required stress and lower maximum strain at higher punch

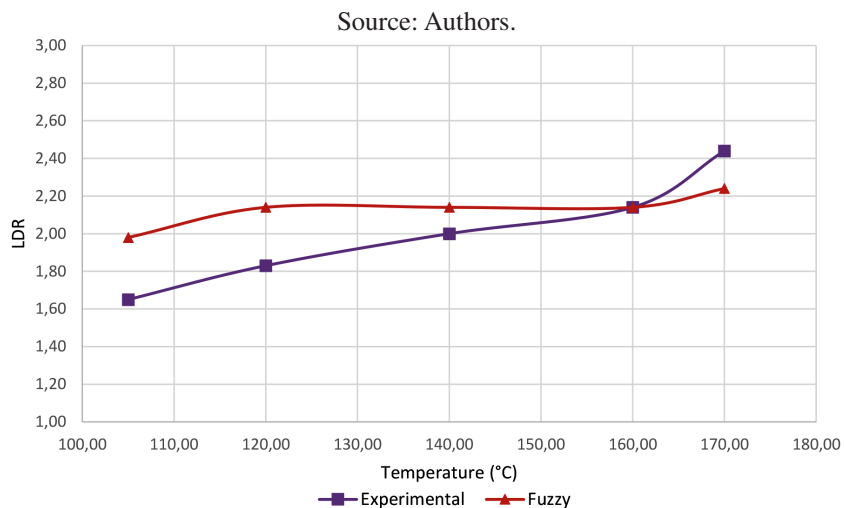


Figure 6. Variant temperature – Thickness: 0.8mm and Velocity: 0.7 mm/s.

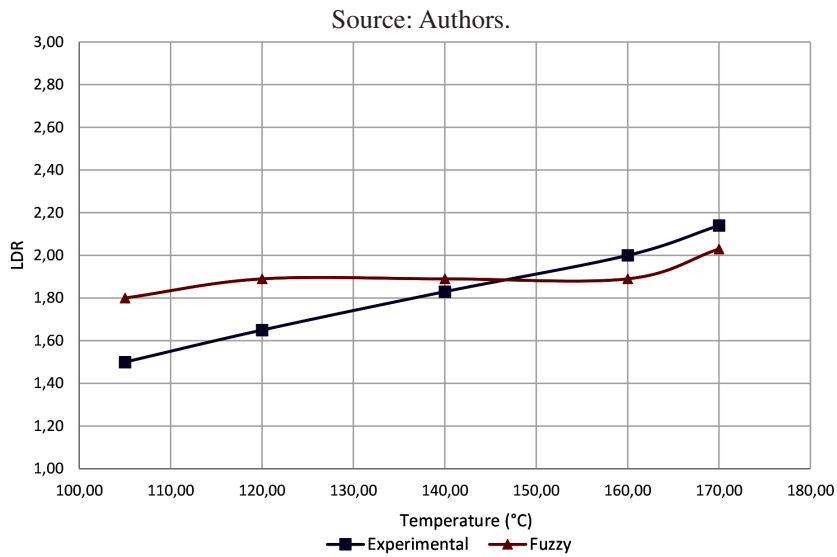


Figure 7. Variant temperature - Thickness: 0.8 mm and Velocity: 1 mm/s.

speeds. Furthermore, tensile tests attested that rising speeds leads to reduced maximum elongations of AZ31 regardless of the working temperature [13]. Additionally, the Fuzzy model achieved an average precision of 96.28%, and the lower accuracy point occurred in $v = 80$ mm/s, reaching 91.95% of precision.

By analyzing Figure 9, it is noticeable that the Fuzzy model almost replicated the experimental results. The average precision obtained was 97.5%, whereas the lower accuracy point occurred in $v = 90$ mm/s,

still resulting in a precision of 95.56%. Moreover, by comparing Figures 8 and Figure 9, it is perceptible that LDR decreases slightly from 1.3 mm to 1 mm of thickness. Since both experiments were conducted using the same load [13], this can be explained by the fact that while a material thickness decreases, its load-carrying capacity decreases. Because of that, preventing failures during forming becomes more complex with thinner sheet thickness [9].

Meanwhile, Figure 10 indicates that LDR peaks at $T = 260$ °C, reaching 2.63, and slightly decreases with

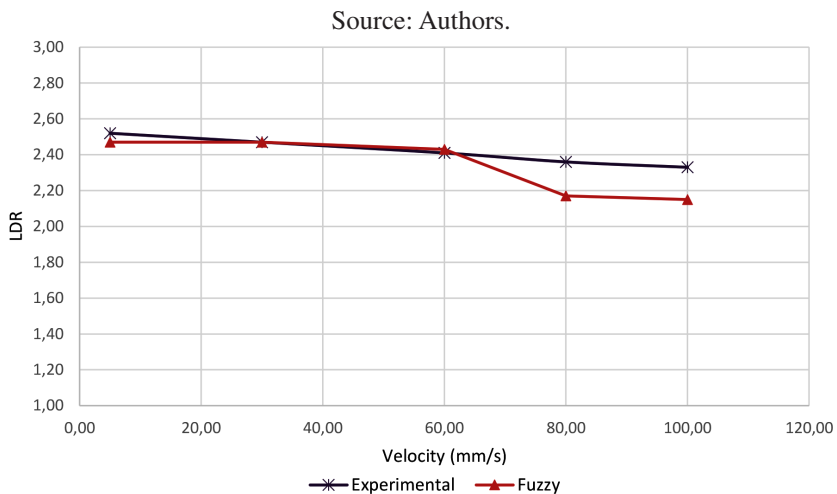


Figure 8. Variant velocity - Thickness: 1.3 mm and Temperature: 200 °C.

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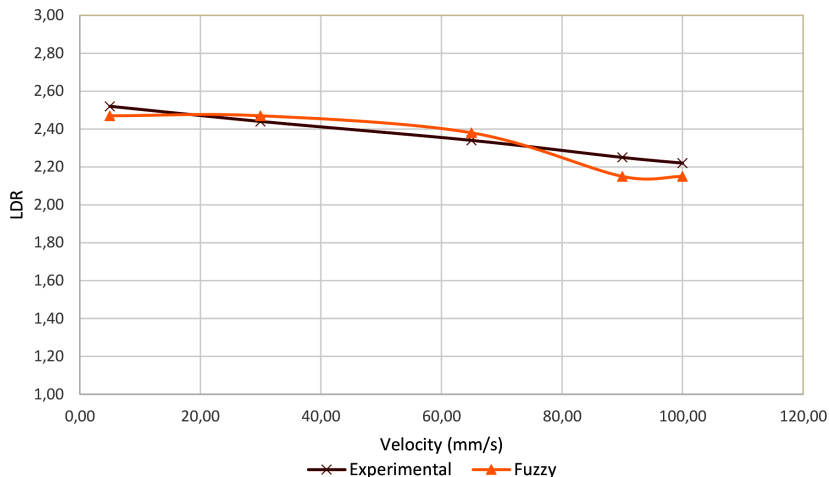


Figure 9. Variant velocity - Thickness: 1mm and Temperature: 200 °C.

temperatures above that [14]. Making a comparison with Figure 5, in which the LDR decreases between 200 °C and 240 °C using a punch speed of 0.5 mm/s and a thickness sheet blank of 0.8 mm, it is possible to infer that higher work temperatures allow higher strain rates, and consequently, becomes possible to use higher velocities. Moreover, the Fuzzy model achieved an average precision of 89.59%, with the lower accuracy point at T = 150 °C with 76.13% precision.

enough to dislocate the deep drawability peak, which moved from T = 260 °C (LDR = 2.63) to T = 212 °C (LDR = 2.56). This behavior could result from thermal conduction differences due to thickness variation, considering that the only difference between the samples was the thickness. Furthermore, the Fuzzy model reached an average precision of 89.43%, with the lower accuracy point at T = 150 °C, with 70.3% precision.

Conversely, Figure 11 shows results obtained from the same study from Figure 10 [14]. It is evident that the reduction of 0.08mm in the thickness was

Figure 12 regards the results of tests performed under temperatures between 150 °C and 300 °C

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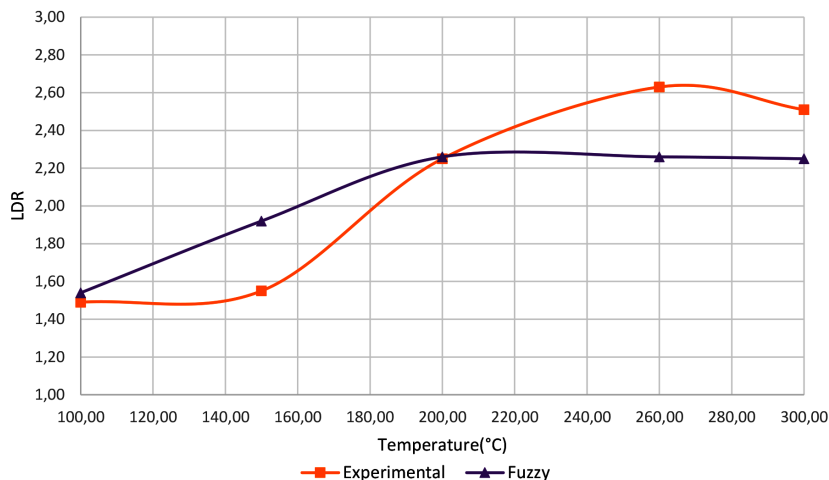


Figure 10. Variant temperature - Thickness: 0.58 mm and Velocity: 3 mm/s.

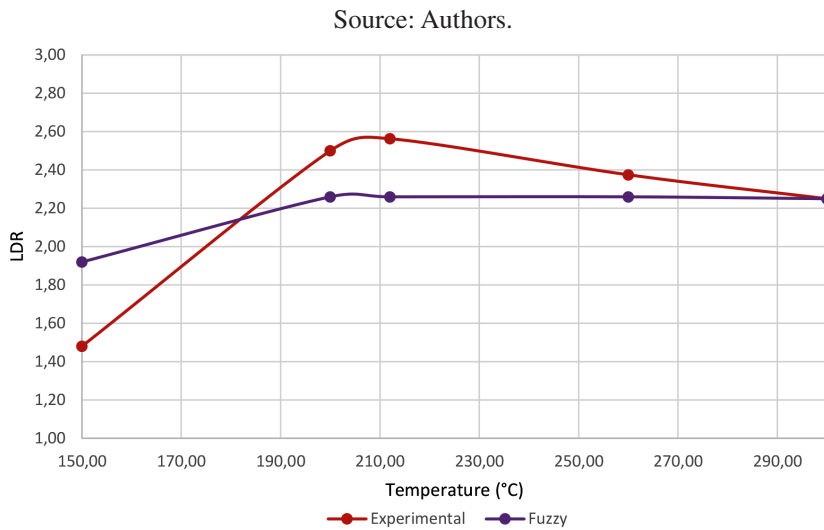


Figure 11. Variant temperature - Thickness: 0.5 mm and Velocity: 3 mm/s.

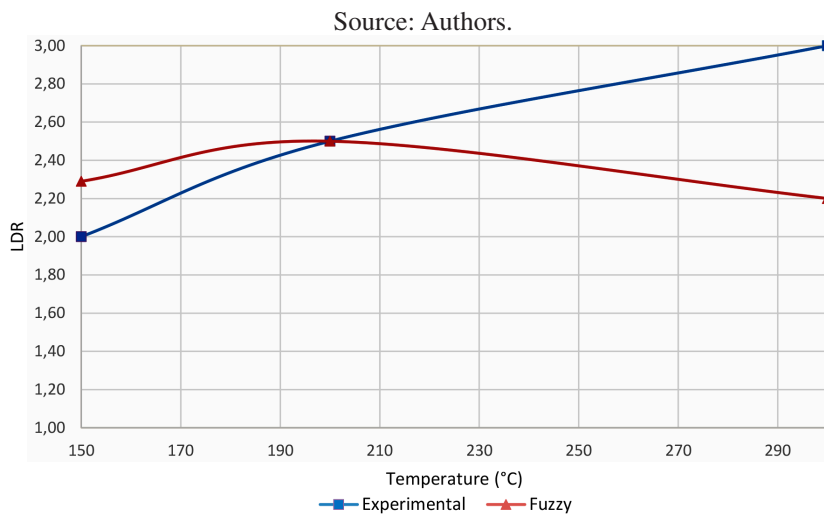


Figure 12. Variant temperature - Thickness: 0.6 mm and Velocity: 15 mm/s.

in a steady drawing velocity of 15mm/s [15]. All LDR achievements were good, starting from T = 150 °C (LDR = 2.0) until T = 300 °C (LDR = 3.0). Comparing LDR peaks at Figures 5 (T = 200 °C, v = 0.5 mm/s); 10 (T = 240 °C, v = 3mm/s) and 12 (T = 300 °C, v = 15mm/s) it is conclusive that there is a trendy: the higher the punch speeds, the higher required work temperature. Consequently, the strain rate sensitivity of Mg alloy is highlighted again by the demonstration that the formability of AZ31 decreases with the increase of the strain rate. Regarding the prediction, the Fuzzy model

reached an average precision of 86.28%, with the lower accuracy point at T = 300 °C, with 73.33% of precision.

Dependency between parameters

The following graphs were generated from the established rules and the assumed ranges to illustrate the dependency between the parameters. In Figure 13, the influence of thickness and temperature on the LDR value is shown. It can be observed that in cases of thin thickness combined with medium to high temperatures - Preferable range - the LDR value

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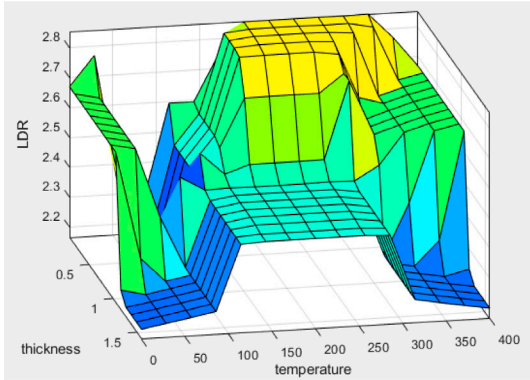


Figure 13. Graphical of LDR interaction as a function of thickness and temperature.

obtained is in the range Better. This value occurs due to the expansion of the magnesium alloy with higher temperatures as a consequence of the activation of the non-basal sliding planes of the HCP structure of AZ31 alloy [17, 41-44].

In Figure 14, the influence of temperature and speed on the LDR is demonstrated. It is possible to notice the sensitivity of AZ31 to the deformation rate. That occurs because the deformation rate influences the hardening behavior and the displacement of the magnesium alloys planes. So, since sliding during plastic deformation requires time, the decrease in speed promotes the deformation capacity, as shown in Figure 5. If the forming speed is excessive, the sliding spacing between adjacent grains is neither

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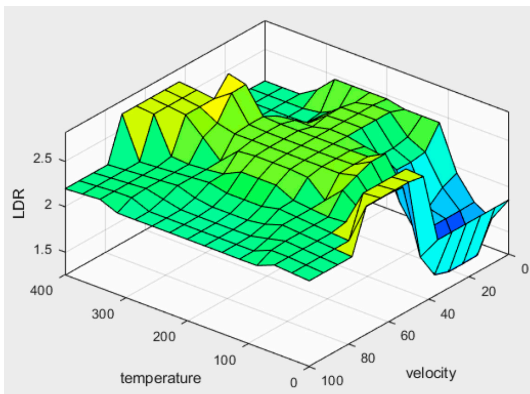


Figure 14. Graphical of LDR interaction as a function of temperature and velocity.

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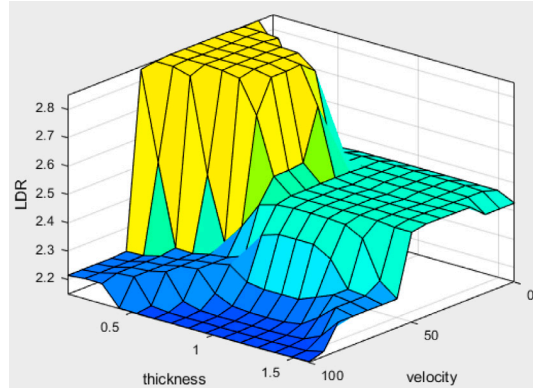


Figure 15. Graphical of LDR interaction as a function of thickness and velocity.

conductive nor continuous, so it is common to have stress concentrations near the grain limit [45].

Figure 14 and Figure 15 show better LDR results under conditions of medium speeds, as expected. Figure 15 depicts the LDR behavior regarding thickness and velocity variation. It is again evidenced that medium velocities are desirable to obtain a good deep drawability.

Figure 16 depicts the rule viewer of the input variables, i.e., thickness, temperature, velocity, and the output variable, i.e., limit drawing ratio of deep drawing process of AZ31. The behavior of each input and output parameter is clearly represented rule by rule.

CONCLUSIONS

In the present study, a Fuzzy model has been developed to predict limit drawing ratio (LDR) during deep drawing of magnesium alloy, AZ31. The conclusions are given as follows:

- 1 The proposed model predicts the LDR with a prediction accuracy of 92.1%. The predicted results are based on the selection of membership function, fuzzy rules, and input process variables. The prediction error was evaluated by comparing the difference between experimental and fuzzy model results to experimental results.
2. The high accuracy achieved is due to the number of assumed rules and ranges, which increase the specificity of the fuzzy model.

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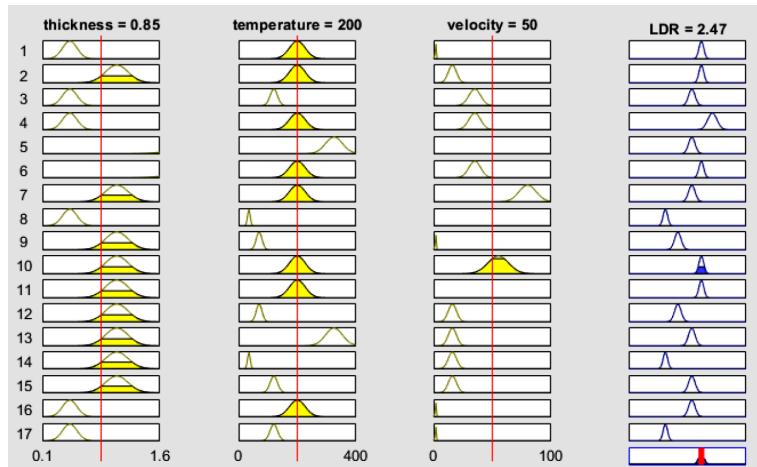


Figure 16. Rule viewer of the present fuzzy modeling of deep drawing process of AZ31.

3. Rule-based Fuzzy modeling is effective and efficient in predicting a wide range of process parameters for the deep drawing process, and it is useful to save resources related to prototyping and destructive tests.
4. A great LDR value for the AZ31 alloy can be achieved by performing a deep drawing process using the parameters' ranges: Sheet thickness (0.1-0.8 mm); Temperature (120°C-290°C); and Velocity (20 mm/s-50 mm/s)
5. A temperature range between 50°C and 90°C is the minimum to ensure a good deep drawability of the AZ31 alloy.
6. Given the agreement with literature and experimental data, the values obtained in this study can be consulted and guide in the choice of initial parameters prior to the conduction of deep drawing experiments with AZ31.

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