[Title page]

Shear Damage Suppression Model of Magnesium Alloy Plates

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Shear Damage Suppression Model of Magnesium Alloy Plates

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Abstract: By shearing Q235 steel, aluminum, and AZ31 magnesium alloy at room temperature, the shear area of Q235 steel and aluminum is found to be relatively flat whereas that of AZ31 magnesium alloy exhibits many defects, such as potholes and cracks. The influence of temperature and strain rate on the critical fracture strain of AZ31 magnesium alloy was obtained using isothermal compression experiment. Results show that high temperature and larger strain lead to large and small critical fracture strains. Therefore, based on the isothermal compression experiment and the effects of temperature and strain rate on the critical fracture strain of AZ31 magnesium alloy, the magnesium alloy plate is heated to 100, 200, 300, and 400 °C, and shearing was conducted after 30 min of heat preservation. Based on the cross-sectional shape and the degree of damage, the optimum shear temperature ranges from 160 °C to 260 °C. At this temperature, the sheared magnesium alloy plate not only obtains an improved cross-sectional shape but also has a small shear corner area. Simultaneously, the shearing basic process model of Q235 steel plate is also obtained based on the industrial test. Furthermore, the shearing basic process model of AZ31 magnesium alloy was acquired based on the elongation ratio of magnesium alloy and Q235 steel under the same process conditions.

Keywords: Shear; AZ31 magnesium alloy; Cross-sectional damage.

1 Introduction

Magnesium alloy has a crucial role in the weight reduction process. Its specific strength is high and achieves the requirements of light weight; thus, the strength of magnesium alloy is sufficient to meet the usage requirements [1]. Magnesium alloy is also widely used in the fields of automobiles and aerospace [2-3]. The easy generation of edge cracks on the magnesium alloy plate during rolling [4-5] and the presence of considerable anisotropy difference between the edge and the middle metal lead to multiple trimming and segmentation shearing during the rolling process [6]. Furthermore, the block must be sheared during its usage. However, its special hcp crystal structure easily leads to the occurrence of secondary damage during the shearing process [7]. At present, the segmentation and shearing blocks of the magnesium alloy plate are mainly sawed. However, this plate has low efficiency, easily ignites sparks, and have considerable hidden dangers in safety. Therefore, developing a low-damage and high-efficiency shearing method for magnesium alloy plates is particularly important.

Accurately analyzing the stress effect characteristics of the shear deformation region is essential to control shear defects and precision shear formation of low-plasticity plates [8-10]. Meanwhile, the quality of shear section reflects the comprehensive properties of shearing machine and material. Blue brittleness occurs in the shear process of carbon steel at 200 °C to 350 °C; the brittleness is improved and the plasticity is reduced, and an improved shear section can be obtained by shearing at this temperature [11]. The shear quality of 2024 aluminum rod can be enhanced by using the shear process of radial clamping and axial compression [12]. High-quality pure plastic shear blanks can be obtained by radial-axial composite compression for chromium zirconium copper bar with poor plasticity [13].

This study focuses on section depression, sag, secondary damage, and edge cracking in the shearing process of low plasticity magnesium alloy plates. The typical grade AZ31 magnesium alloy plate with small shearing deformation zone is taken as the research object. Based on the precise control of the area affected by the shear stress effect and taking the adjustable property of shear deformation region as the starting point, the cross-scale effect of the magnesium alloy material of hcp crystal structures is initially studied under shear stress. The influence of billet and shearing process parameters on

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shear stress effect is then investigated. Finally, the analysis method of rolling shear force based on the shear stress effect is studied to determine the precision shear basic model of magnesium alloy plates.

2 Experimental and establishment of shearing process model

2.1 Shear experimental

At room temperature, shear the Q235 steel, aluminum, and as-cast AZ31 magnesium alloy plate with a thickness of 5mm using the disc shear with a small shear deformation zone, and observe the shape and damage of the shear section by scanning electron microscope. The differences between shear deformation of magnesium alloy and other metal materials were analyzed. The as-cast AZ31 magnesium alloy was cut into cylinders with a diameter of 7 mm and a height of 7 mm. At 250, 300, 350, and 400 °C, the critical fracture strains were obtained by using Gleeble-3800 thermal simulator at strain rates of 0.005, 0.05, and 0.5.The AZ31 magnesium alloy plate was heated to 100, 200, 300, and 400 °C by vacuum heating furnace for 30 min, and the magnesium alloy plate was hot-sheared by disc shear. The ZEISS scanning electron microscope was used to observe the appearance of fractures, the shear experimental shown in Fig. 1. Simultaneously, the ultrafine field microscope is used to observe the range of the corner area of the shear section and obtain optimum shear temperature of AZ31 magnesium alloy, providing the theoretical basis for the shear of magnesium alloy plates.

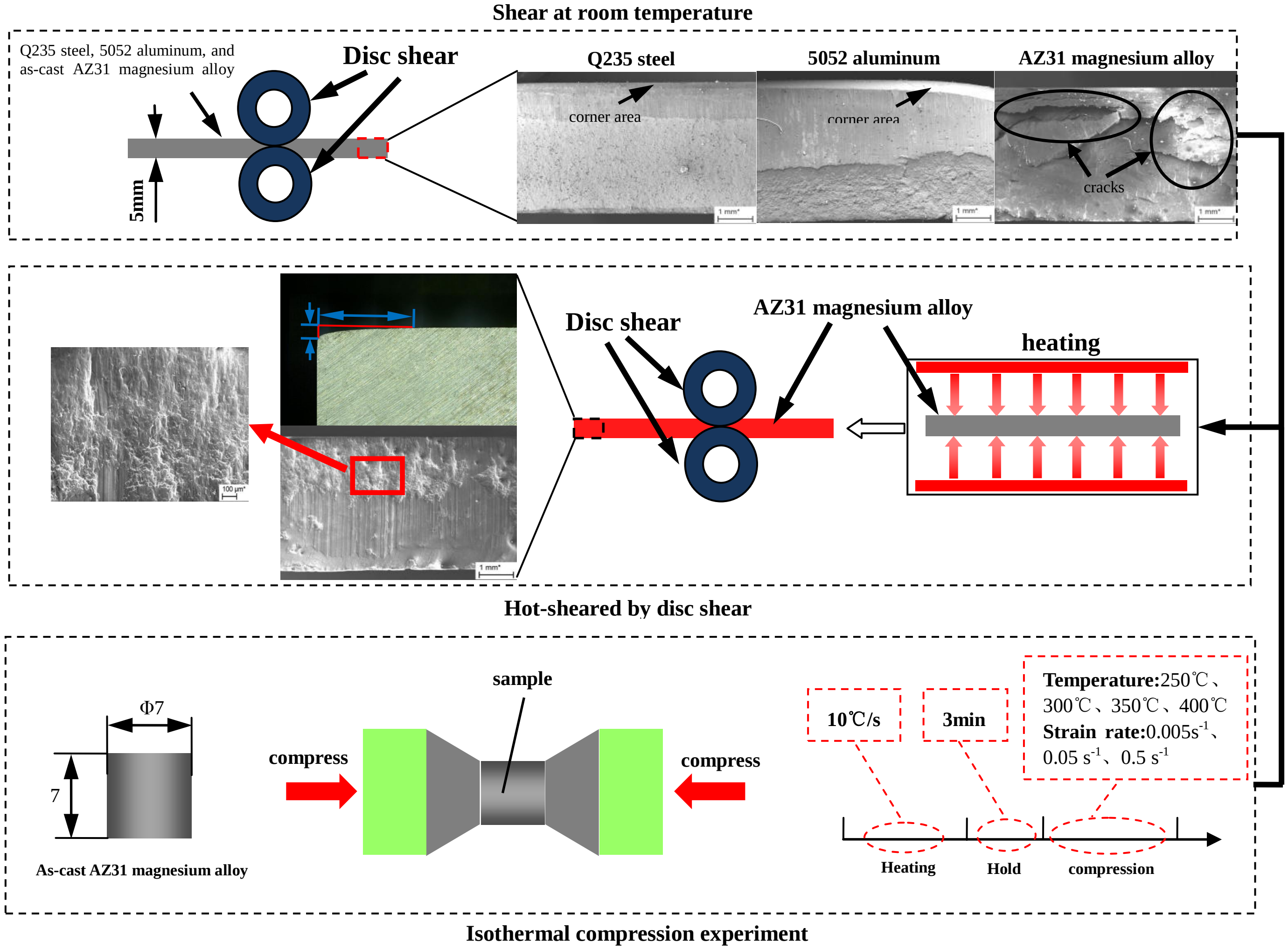

Fig. 1. Schematic diagram of the Shear experimental

2.2 Adjusting model of shearing edge gap

The shear deformation ability is mainly related to the plasticity of the material, and the elongation is one of the indicators that reflect the plasticity of the material. The shearing basic process model of Q235 steel plate is also obtained based on the industrial test. Furthermore, combined with the change law of magnesium alloy shear damage with temperature, the shearing basic process model of AZ31 magnesium alloy was acquired based on the elongation ratio of magnesium alloy and Q235 steel under the same process conditions.

3. Results and discussion

3.1 Sheared profiles at room temperature

The Q235 steel, 5052 aluminum, and as-cast AZ31 magnesium alloy were sheared at room temperature, and their sheared profiles are shown in Fig. 2.

The sheared profiles of Q235 steel and aluminum comprise corner, smooth, and tearing areas. Q235 steel has smaller corner and smooth areas, and larger tearing areas than those of the aluminum. However, the damage degree of the tear area is evidently smaller than that of aluminum. Given the high hardness of the Q235 steel, the deformation range on both sides of the deformation area is small, the deformation resistance of the plate end is strong, and the corner area is small during shear deformation. Tearing occurs when the shear depth is small due to the large deformation resistance. Given the low hardness of aluminum, the metal on both sides of the deformation area also deforms in the event of shear deformation; thus, the corner area is large. The tearing phenomenon of the profiles will only occur when the shear deformation is deep due to its weak deformation resistance.

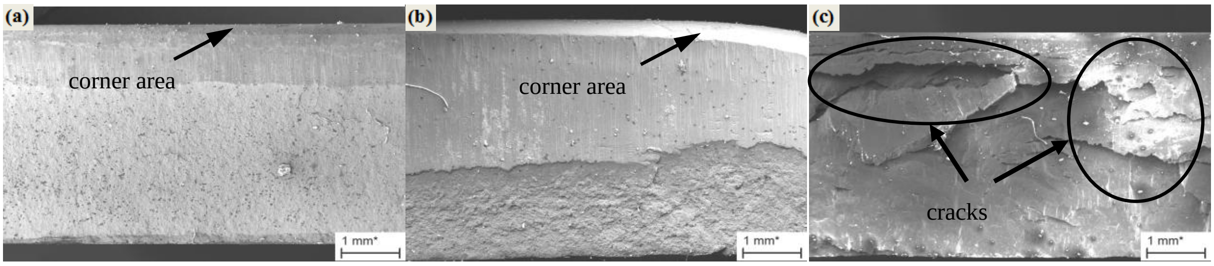

Fig. 2. Comparison of typical sheared edge profiles obtained at room temperature: (a)Q235 steel，(b) aluminum alloy，(c) as-cast AZ31 magnesium alloy.

Large-scale cracks occur in AZ31 magnesium alloy during shear deformation at room temperature due to its poor plastic deformation capability. The fracture mainly demonstrates brittles when subjected to shear force. The brittle fracture of the material should have an improved cross-sectional morphology, but the fracture between crystals of magnesium alloy material at low temperatures cannot easily occur. When subjected to the shearing force, some of the small crystals in the matrix are extracted from the matrix of the material, resulting in many cracks and pothole defects. Moreover, the internal viscosity of the material is reduced at low temperature; the damage cannot be weakened by the metal flow after the damage; therefore, the shear damage is serious at room temperature.

3.2 Critical fracture strain of AZ31 magnesium alloy

At 250, 300, 350, and 400 °C, the critical fracture strains of AZ31 magnesium alloy at strain rates of 0.005, 0.05, and 0.5 were obtained by isothermal compression, as shown in Table 1. The critical fracture strain of the material increases with the temperature. The critical fracture strain is only reflected after the brittle deformation of materials because their plastic deformation process does not affect the critical fracture strain. When the temperature is raised from 300 °C to 350 °C, the increase in critical fracture strain is the largest; the minimum and maximum increases are 0.09 and 0.12, respectively. When the temperature rises from 250 °C to 300 °C and 350 °C to 400 °C, the increase in critical fracture strain is small; the maximum and minimum increases are 0.05 and 0.02, respectively. When the isothermal deformation temperature of magnesium alloy is increased from 300 °C to 350 °C, the plastic deformation capability of the material is considerably improved; thus, the critical fracture strain mostly changes during this temperature range. When the temperature is lower or higher than this temperature, the temperature change has slight effects on the plastic deformation of the material. Therefore, the changes in critical fracture strain are small.

Table 1 Critical damage values of AZ31 magnesium alloy under different conditions

Temperature $T(^{o}C)$	250			300			350			400		
Strain rate $\dot{\varepsilon}(s^{-1})$	0.005	0.05	0. 5	0.005	0.05	0. 5	0.005	0.05	0. 5	0.005	0.05	0. 5
Critical fracture strain C_f	0.32	0.28	0.25	0.36	0.31	0.28	0.48	0.4	0.38	0.5	0.45	0.41
LnZ	58.1	60.5	62.8	47.6	49.9	52.2	40.1	42.4	44.7	34.4	36.7	39

The strain rate also has an evident effect on the critical fracture strain of AZ31 magnesium alloy. Overall, with the increase in strain rate, the critical fracture strain is small, but the specific range of change is also related to the deformation temperature. When the strain rate is 0.005, 0.05, and 0.5 isothermal compressions, the changes in critical fracture strain at 250 and 400 °C are small and those at 300 and 350 °C demonstrate considerable changes. This phenomenon shows that the strain rate has slight effects on the critical fracture strain at low and high temperatures whereas that at medium and high temperatures has a considerable influence on the critical fracture strain.

3.3 Sheared profiles of AZ31 magnesium alloy

The shear corner area of AZ31 magnesium alloy at 100, 200, 300, 400 °C is shown in Fig. 3.

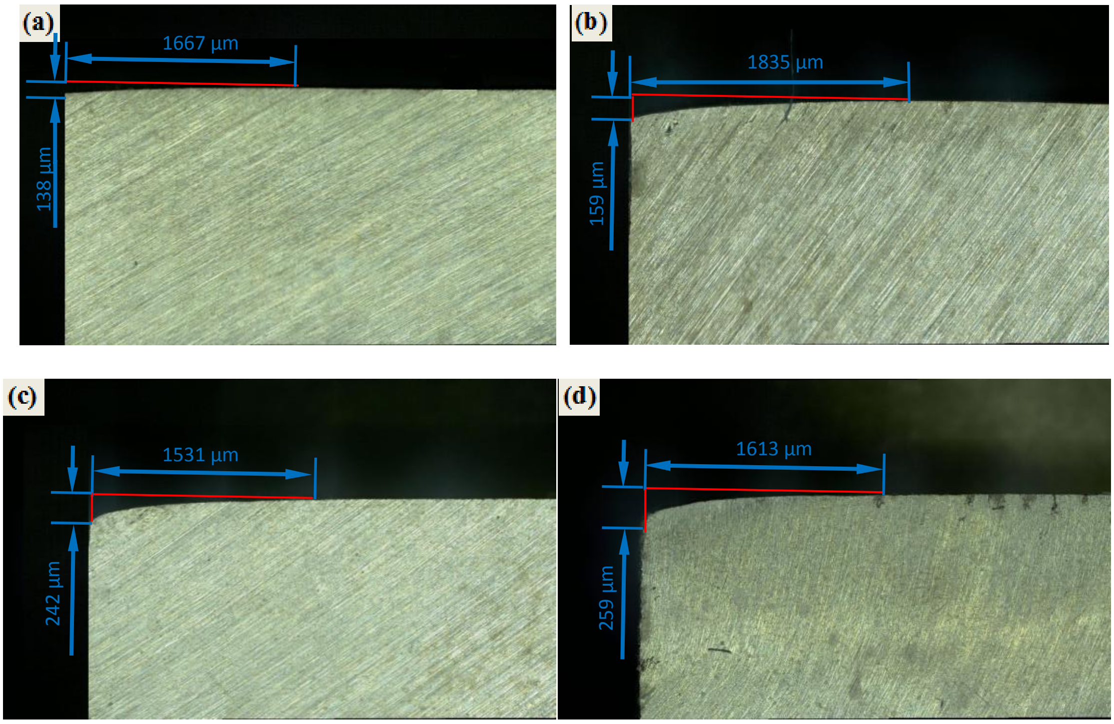

Fig. 3. Comparison of Fillet area obtained at different temperature of AZ31 magnesium alloy: (a)100℃, (b)200℃, (c)300℃, (d)400℃

The height of the corner area increases with the shear temperature. When the tapping temperature of the plate increases from 200 °C to 300 °C, the height of the shear corner area considerably varies ; when the tapping temperature of the plate increases from 100 °C to 200 °C and 300 °C to 400 °C, the height of the corner area slightly changes. The plastic deformation capability of magnesium alloy is substantially improved due to the high temperature change of magnesium alloy, and the height of the shear corner area evidently increases with the temperature. When the recrystallization temperature is approximately 250°C, the plastic deformation capability considerably changes. Therefore, the height of the corner area near this temperature shows remarkable changes.

The width of the corner area increases when the temperature is 100 °C to 200 °C and decreases first and then increases when the temperature is 200 °C to 400 °C. When the temperature is lower than the recrystallization temperature, the effect of temperature change on the plastic change of plate metal is unclear. Therefore, the deformation resistance of the plate metal is large when subjected to shear force, leading to the large width of the corner area of the plate. When the temperature rises above the recrystallization temperature, the plastic deformation capability is fully improved, and the deformation resistance of the plate is reduced. During shear deformation, the main deformation direction is plate thickness direction, which leads to a decrease in the width of corner area.

The damage of shear deformation profiles of magnesium alloy at 100, 200, 300, and 400 °C is shown in Fig. 4. Compared with the sheared profiles at room temperature, the shear of magnesium alloy plate can obtain improved cross-sectional morphology after heating. Moreover, no large-scale cracks occurred, and some micro-cracks, potholes and bubble-like bulges were observed. The magnesium alloy quickly dissipates heat due to the removal of the plate metal from the heating furnace to the complete shearing time. Therefore, the temperature described herein is the tapping temperature, and the actual shear temperature is approximately 40 °C to 60 °C lower than the tapping temperature.

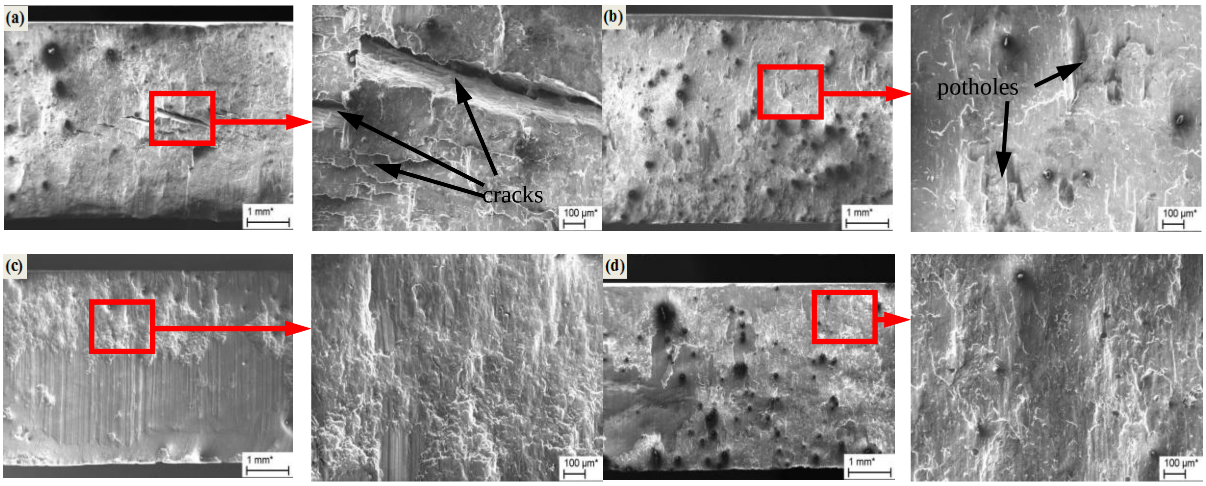

Fig. 4. Comparison of typical sheared edge profiles obtained at different temperature of AZ31 magnesium alloy: (a)100 °C, (b)200 °C, (c) (c)300 °C, (d)400 °C

Cracks appeared in the profiles of AZ31 magnesium alloy plate after shearing at 100°C, and large bubble-like bulges were observed. Moreover, the quality of the profiles was poor, no macroscopic visible smooth area existed, and the flatness of the sheared profiles remained poor. No macroscopic crack appeared in the profiles of AZ31 magnesium alloy plate sheared at 200 °C. However, many potholes and bubble-like bulges remained, the flatness of sheared profiles was improved, and the central metal bulges emerged in the direction of plate thickness. The profile quality of AZ31 magnesium alloy plate sheared at 300°C is the best; smooth areas were observed, no large cracks and potholes were found in the tearing area, and the flatness of the sheared profiles was considerably improved. Large cracks, potholes, and other defects were absent in the profiles of AZ31 magnesium alloy plate sheared at 400 °C. However, many bubble-like bulges were observed, and the flatness of the sheared profiles remained.

3.4 Basic model of precise shearing

When the magnesium plate is directly sheared at room temperature, brittle fracture may occur after the shear force of the plate shearing machine. Numerous secondary crack damage defects also appear in the sheared profiles. The deformation does not easily occur due to the special crystal structure of the magnesium alloy plate, and the fracture phenomenon easily breaks when the magnesium alloy plate is subjected to large applied shearing stress. Moreover, the poor deformability of the plate can lead to secondary damage during the shearing fracture process. This phenomenon can cause numerous defects in the shear profiles of the plate.

The quality of the shear profiles can be considerably improved by heating the magnesium alloy plate before shearing. Obtaining improved shear profiles is easy with the increase in temperature. The sheared profile quality is the best when the temperature is between 160 °C to 260 °C due to the absence of crack defects in the sheared profiles. The worse deformation capability of magnesium alloy is observed at low temperatures. The occurrence of inter-crystal fracture is difficult, and the brittle fracture is the main fracture situation. When the temperature is high, the internal viscosity of the plate increases and the shearing profile quality is poor. Therefore, the sheared profile quality is best obtained after the temperature is between 160 °C to 260 °C.

1)The mathematical model of shearing edge gap and steel plate thickness is as follows.

Table 2 shows the optimized disc-shearing process parameters to track the accumulation of production practice for half a year in a medium-sized plate factory of a steel company.

Tab 2 Measured disc shearing process parameters（Q235）

Steel plate thickness（mm）	10	12	14	16	18	20	22	25	28	30
amount of scissors overlapping（mm）	3.5	4.5	5.3	6.5	7.0	8.3	9.5	11.5	13.5	14.0
blade clearance（mm）	1.7	2.0	2.3	2.6	3.2	3.6	4.0	4.5	4.8	5.0

The multinomial curve fitting is conducted by using MATLAB software based on the measured data to achieve the rapid initial setting of disc shearing process parameters when the metal specifications of different materials are changed.

The analysis results show that the primary function is the most ideal, and the mathematical model of disc shear overlap corresponding to the aforementioned measured data is:

$$\mathrm{S} = 0.5476 \times h - 2.3054,$$

where S is overlap, and h is thickness of the plate.

The same method is applied to obtain the mathematical model of the lateral shear gap of disc shearing edge corresponding to the above measured data results in the following:

$$\delta = 0.1845 \times h - 0.1934,$$

where δ is the lateral gap of shearing edge, and h is thickness of the plate.

2)The mathematical model of shearing edge gap and cumulative shear is as follows.

A new shearing edge will wear with the increase in cumulative shear amount. When shearing a steel plate of the same thickness, gradually reducing the shearing edge gap is necessary. Suppose a new shearing edge can shear the steel plate with the cumulative area of $\mathrm{A}_{\mathrm{max}}\mathrm{mm}^2$ as the amount to be consumed. The total area of the sheared profiles is A, and $(\mathrm{A}_{\mathrm{max}} - A)/\mathrm{A}_{\mathrm{max}}$ can be regarded as the residual shearing capacity coefficient. Therefore, the mathematical model between the optimal shearing edge gap and the shear profile area A after the accumulation of a certain amount of shear profile area is as follows:

$$\mathrm{GAP} = \frac{A_{\mathrm{max}} - A}{A_{\mathrm{max}}} \times \mathrm{GAP}_0,$$

where GAP_0 is the best clearance for the new shearing edge.

A and $\mathrm{A}_{\mathrm{max}}$ are determined by tracking records in production practice for specific equipment, and $\mathrm{A}_{\mathrm{max}}$ is a constant. Taking the average value according to practice records, the GAP of any time can be calculated.

3)The mathematical model of shearing edge gap and shear material properties is as follows:

During the metal shearing, the metal near the point of action of the shear force will slip with the increase in shear force. When the plastic deformation of the metal on the upper and lower surfaces of the shearing edge reaches the limit-fracture strain, cracks will appear at the point of shear force. With the further approach of the upper and lower tool holder, cracks will also merge in the internal metal fiber. The fracture crack will propagate along the line between the upper and lower shear force points in the adjacent metal, reaching the fracture strain value. When the two broken lines meet, the shear undergoes fracture.

Therefore, the plasticity of shear material is mainly exhibited in the shear process. The two indexes reflect the plasticity of the material elongation and area reduction, which can be transformed into each other. The mathematical model of shearing edge gap and shear material properties can be expressed as follows:

$$\mathrm{GAP} = \frac{\mathrm{GAP}_0}{\mathrm{k}_1} \ ,$$

Where k_1 is ratio of the elongation of the metal to be sheared to Q235.

4)The mathematical model of shearing edge gap and shear temperature is as follows.

When the steel plate is sheared, the temperature increases, the strength reduces, and shear defects, such as shear deformation and glitches, are likely to occur. When the temperature is high to affect shear quality, the shearing edge gap can be adjusted properly. The practice shows that when the shear temperature is less than 150 °C, the temperature does not affect the shear quality. Based on 150 °C, when the temperature is increased by 50 °C ,the shearing edge gap should be reduced by 0.05-0.1 mm based on the steel plate thickness to ensure shear quality. The mathematical model of shearing edge gap and shear temperature is

$$\mathrm{GAP} = \mathrm{k}_2 \frac{T-150}{50},$$

where k_2=0.05-0.1 mm, and *T* is the temperature of the steel plate for shearing.

Based on the above experimental results and industrial tests, a basic shearing process model for magnesium alloy plates was established:

$$\mathrm{GAP(S)} = \frac{A_{\max}-A}{A_{\max}} \times (0.5476 \times h - 2.3054) \times \frac{1}{\mathrm{k}_1} - \mathrm{k}_2 \frac{T-150}{50} \quad (1),$$

$$\mathrm{GAP}(\delta) = \frac{A_{\max}-A}{A_{\max}} \times (0.1845 \times h - 0.1934) \times \frac{1}{\mathrm{k}_1} - \mathrm{k}_2 \frac{T-150}{50} \quad (2).$$

(1), (2): GAP(S): adjustment model of the overlap optimal shearing edge; GAP(δ): adjustment model of the optimal shear edge lateral gap.

4.Conclusions

The following conclusions can be drawn from the present study:

(1) When the magnesium plate is sheared directly at room temperature, the brittle fracture easily occurs after the shearing force of the plate, and many secondary crack damage defects appear in the sheared profiles. The critical fracture strain of AZ31 magnesium alloy plate increases with the temperature in the range of 250 °C to 400 °C. The critical fracture factor decreases with the increase in strain rate in the range of 0.005 to 0.5, and the temperature range of maximum variation is in the range of 300 °C to 350 °C.

(2) The quality of the shear profiles can be considerably improved by heating the magnesium alloy plate before shearing. With the increase in temperature, obtaining improved shear profiles is easy. When the temperature is between 160 °C to 260 °C, the quality of the shear profiles is the best, and no crack defects are observed in the shear profiles.

(3) Based on the above experimental results and industrial tests, a basic shearing process model for magnesium alloy plates was established:

$$\mathrm{GAP(S)} = \frac{A_{\max}-A}{\mathbf{A}_{\max}} \times (0.5476 \times h - 2.3054) \times \frac{1}{\mathrm{k}_1} - \mathrm{k}_2 \frac{T-150}{50} \quad (1),$$

$$\mathrm{GAP}(\delta) = \frac{A_{\max}-A}{A_{\max}} \times (0.1845 \times h - 0.1934) \times \frac{1}{\mathrm{k}_1} - \mathrm{k}_2 \frac{T-150}{50} \quad (2).$$

(1), (2): GAP(S): adjustment model of the overlap optimal shearing edge; GAP(δ): adjustment model of the optimal shear edge lateral gap.

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Authors' Contributions

ZH provided guidance for the whole research. GY and CQ designed the experiments and wrote the initial manuscript. RW and MS assisted with sampling and laboratory analyses. All authors read and approved the fnal manuscript.

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Competing Interests

The authors declare no competing financial interests.

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