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ORIGINAL ARTICLE

Analysis of the forming behaviors of magnesium alloy AZ31 by vaporizing metal foils

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Abstract
Vaporizing metal foils is a relatively new high-speed material processing technique which can improve the material's forming limit and reduce the springback. This study aims to investigate the forming behaviors of sheet metals by vaporizing metal foils. A simple analytical model to calculate the energy efficiency of this forming method is firstly introduced. The forming behaviors of magnesium alloy AZ31 is analyzed by free bulging tests at room temperature. Besides, the mechanical behaviors of magnesium ally AZ31 is compared with that of aluminum alloy EN AW-6082. The experiments indicate that the magnesium alloy AZ31 exhibits good formability by vaporizing metal foils without heating treatment. Therefore, it is feasible to conduct plastic forming process of magnesium alloy ZA31 at room temperature, which is different from the traditional warm forming method for magnesium alloy.

Keywords Magnesium alloy · Energy efficiency · Metal forming · Vaporizing foils

1 Introduction

Applying high-speed forming methods like electromagnetic forming, forming limits can be exceeded to higher value, additionally less spring back and low-cost tools, compared to quasi static forming methods [1]. Three impulse forming approaches which are available for sheet metal forming are distinguished, explosive forming, electro-hydraulic forming and electro-magnetic forming [2]. However, there are also some limitations of these forming methods, such as the high safety protection (explosive forming) and the relatively high costs (enclosure for electro-hydraulic forming and actuators or forming coils with limited lifetime for electro-magnetic forming). Vaporizing metal foils could be a new solution for the issues of the traditional high-speed forming methods. Thin conductors such as metallic wire and foil can be vaporized under high-density current to produce mechanical pulse and shock waves, supplying impulsive loading for metal forming. The endure time of the entire forming process by vaporizing foils is in the range of microseconds. Therefore, this forming approach belongs to high-speed forming methods and possesses the advantages of them. Besides, vaporizing foils requires no explosives and coils, which makes it a reliable material processing technique with low cost.

Vaporizing metal foils is firstly applied in some basic metal forming processes, for example shearing and embossing [3, 4]. The forming results of different parts identify that vaporizing metal foils is a feasible manufacturing approach for metals. This technique is also used to join different metals through solid welding method. It requires no heating and there are little intermetallic compounds generated during the welding process [5, 6]. The metallographic structure at the interface of the two metal layers is analyzed as well. The joining strength at the interface exceeded that of the parent materials. Vaporizing metal foils seems a potential alternative to the joining issue of dissimilar metals. Pressure distributions realized by vaporizing metal foils are also investigated [7–10]. Tailored pressure distributions and double-direction pressure distributions are generated using various combinations of process parameters of vaporizing foils. The tailored pressure distribution could reduce the rebound effect in high-speed forming and the double-direction pressure distribution could be used for profile forming as shown in Fig. 1.

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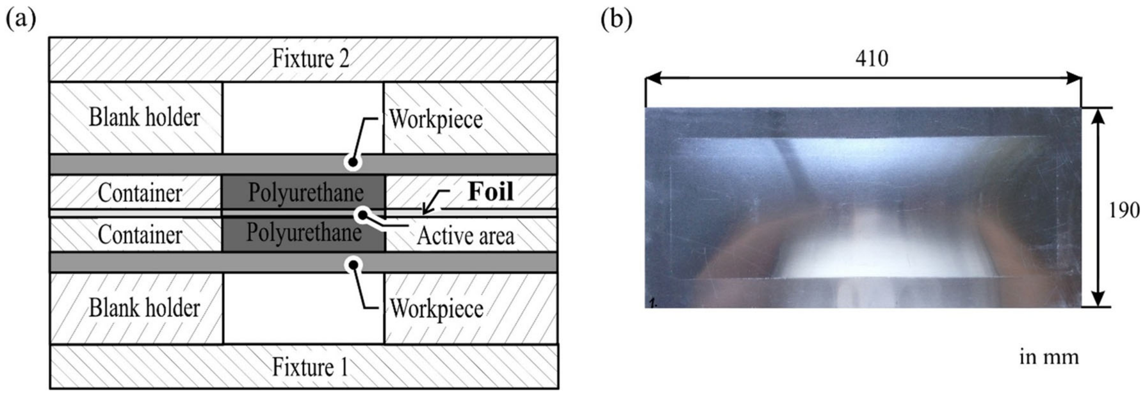


Fig. 1 **a** Process principle of double-direction pressure distribution. **b** An example part

Magnesium alloy has hexagonal close packed lattices structure. Due to the limited slip systems, magnesium alloy exhibits poor plastic formability at room temperature. Hence, heating treatment is mandatory for magnesium alloy to be plastic manufactured [11]. It has been found that magnesium alloys can be warm formed in the temperature range of 120 to 170 °C with the limit drawing ratio of 1.4 to 2.6 in deep drawing process, on the condition that the magnesium alloy sheets have been properly rolled and annealed. Also, the limit drawing ratio is influenced strongly by punch speed in the warm deep drawing of magnesium alloys. With decreasing punch speed from 30 mm/min to 6 mm/min, the LDR increased remarkably from 2.2 to 3.25 at blank temperature 180 °C and increased from 2.8 to 3.375 at blank temperature 230 °C. The effect of upper-die temperature on the formability of AZ31 magnesium alloy sheet in stamping process is investigated using forming limit curves under different temperatures as well. The formability of the magnesium alloy decreases significantly as upper-die temperature drops [12]. The heating process for magnesium alloy increases the manufacturing cost and processing steps, which negatively influences the application of magnesium alloy in industry [13, 14].

This study aims to investigate the forming behaviors of magnesium alloy AZ31 at room temperature. Vaporizing metal foils is applied as the processing technique for magnesium alloys. A simple analytical model to calculate the energy efficiency of sheet metal forming by vaporizing foils is introduced. The deformation of magnesium alloy AZ31 is analyzed. A comparison between magnesium alloy and aluminum alloy is obtained. The results indicate that it is possible to achieve good formability of magnesium alloy at room temperature through vaporizing metal foils.

2 Materials and methods

This study is conducted experimentally using a Maxwell capacitor bank with a maximum charging energy 32 kJ. The experimental setup consists mainly of two functional parts: forming components and the connection components as illustrated in Fig. 2. The fixture and the blank holder are made of steel. Polyurethane plate is applied to transfer the pressure from the generated gas or plasma through vaporization to the sheet metal due to its excellent elasticity. After the entire forming process is finished, the polyurethane plate could be reused for another operation. The metal foil is connected with the coppers which are joined together with the electrodes. Therefore, a complete electric circuit is generated. The metal

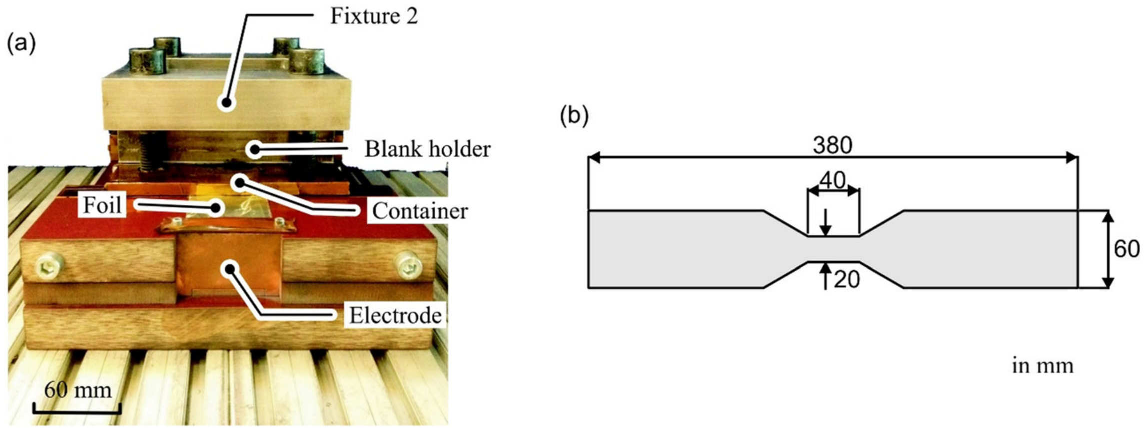


Fig. 2 **a** Experimental setup. **b** Foil specimen

Table 1 Material parameters applied in vaporizing metal foils

Material	Metal foil	Polyurethane	AZ31	EN AW-6082	EN AW-1050
Thickness	0.06 mm	3 mm	1 mm	1 mm	1 mm

foil is functioned as an actuator for the vaporizing process. After the capacitor bank is discharged, the current passes through the metal foil and heats it. Under the Joul heating effect, the metal foil reaches high temperature and finally is vaporized. The vaporization occurs after the discharge of the capacitor bank from a dozen to several tens of seconds. The generated gas or plasma impacts on the sheet metal and provides shock pressure to the deformation of it. The entire forming process lasts only several tens microseconds. Aluminum alloy is applied as the metal foil material. Magnesium alloy AZ31 and aluminum alloy EN AW-6082 are used as the workpieces for the sheet metal-forming processes. The specific material parameters are listed in Table 1. Aluminum foil is applied as the vaporization actuator. The specific dimensions of the foil specimens are displayed in Fig. 2. The workpiece material for the analysis of energy efficiency is aluminum alloy EN AW-1050.

Free bulging test is applied to investigate the forming behaviors of sheet metals by vaporizing foils. The process principle is illustrated in Fig. 3. There is no plate placed on top of the workpiece. After the metal foil is vaporized, the workpiece is imposed on shock pressure and achieves plastic deformation. Due to the open area above the sheet metal, the workpiece could move freely until the plastic deformation terminates. As a result, the final bulging height of the workpiece could indicate the shock pressure amplitude of the pressure pulse. In this study, the shock pressure amplitude is varied using different charging energies of the capacitor bank, for example, 3 kJ, 4 kJ, and 4.8 kJ. The forming behaviors of the magnesium alloy AZ31 is examined through the free bulging tests with different pressure pulses. An example part is presented in Fig. 3 as well. The final bulging heights of the parts are measured by means of GOM Atos optical measurement system.

3 Analysis of the energy efficiency

In the forming process by vaporizing metal foils, the pressure used for the workpiece deformation is essentially induced by the metal gas or plasma. During the discharge process of the capacitor bank, the metal foils are heated and finally vaporized. The generated metal gas or plasma provides pressure for metal forming work. At the same time, some energy is lost as lights and in other ways. A higher utilization of the metal gas or plasma results in a greater energy efficiency for the metal forming work. In order to understand the working mechanism of this forming technique, it is necessary to analyze the energy efficiency in the forming process. In this section, an analytical method to calculate the energy efficiency is introduced. Consider the operability of the analytical model, the quasi-static material model is applied. Hence, it is convenient to calculate the energy efficiency by means of this method. But the accuracy of this analytical method is damaged due to the neglection of the strain rate sensitivity of the material. The analytical model is used to estimate the energy efficiency roughly. Take the double-direction pressure distribution as research objects and a further objective is to identify the metal forming energy of the two pressure modes in double-direction pressure distribution and make a comparison of the energy efficiency generated in both pressure modes [9].

A useful quantity for describing the energy or work needed to produce deformation is the unit energy. The specific energy per volume is defined as the integral of stress times strain [15].

$$E_f = \int \sigma d\varepsilon \tag{1}$$

The usefulness of the unit energy comes with the ability to calculate the energy required to deform a material by

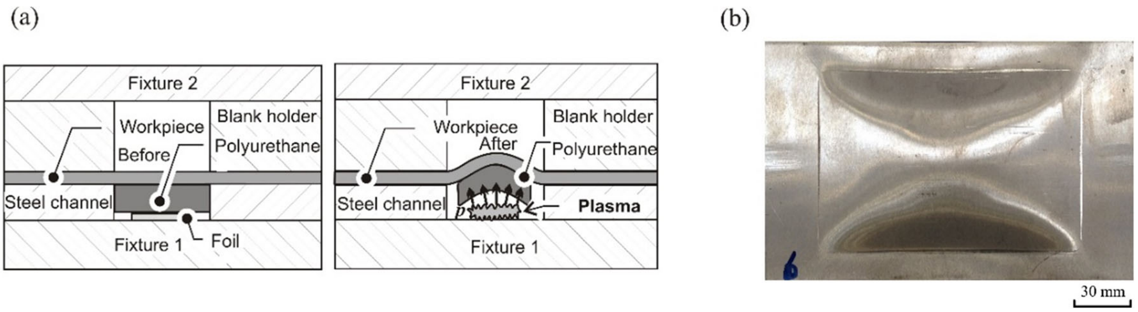


Fig. 3 **a** Process principle of free bulging test. **b** An example part of magnesium alloy AZ31

multiplying the unit energy and the material volume. In this work, only the unit energy is considered since the volume keeps constant for all the workpieces.

An approach to visualize the unit energy is by viewing the integral as the area under the stress-strain curve. In order to simplify the analysis process, the effect of the strain rate on the deformation behavior is neglected since all the experiments are conducted under a high-forming speed. In this study, the stress-strain curve achieved from the quasi-static tensile test is employed to calculate the plastic work in the forming parts.

In order to determine the plastic strain for the calculation of the unit energy, the parts are digitalized in GOM Atos optical system and the profiles of the parts in the horizontal direction and vertical direction are measured. The acquired profile curves could be fitted with a four polynomial function as shown in Fig. 4. Therefore, the profile length could be calculated with the following equation.

$$s = \int_a^b \sqrt{1 + \left[f'(x)\right]^2} dx \tag{2}$$

Take into the account of the geometry of the forming part, the thinning effect concentrates mainly on the plastic hinges. For most areas of the part, the variation of the thickness is very small. In order to simplify the calculation process, the strain in the thickness direction is neglected. With the knowledge of the profile lengths, the average plastic strain of the forming part could be achieved with the following expression.

$$\begin{cases} \varepsilon_1 = \ln \dfrac{l_1'}{l_1} \\ \varepsilon_2 = \ln \dfrac{l_2'}{l_2} \\ \varepsilon_3 = 0 \end{cases} \tag{3}$$

where l_1 and l_2 are the original horizontal and vertical lengths of the workpiece, l_1' and l_2' are the corresponding lengths of the forming part as shown in Fig. 4b. Therefore, the corresponding equivalent strain could be determined.

$$\overline{\varepsilon} = \frac{1}{\sqrt{2}} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2} \tag{4}$$

Figure 5 describes the true stress-strain curve from the tensile test at room temperature. As discussed above, the plastic work during the deformation could be determined as the integral of stress times strain which could be visualized as the area under the stress-strain curve.

In order to simplify the analytical process, the area under the stress-strain curve could be approximately calculated with a trapezoidal diagram as shown in Fig. 5. Therefore, the energy efficiency which indicates the ratio of the energy needed to produce deformation to the initial charging energy of the capacitor bank.

$$\eta = \frac{E_f}{E_c} \tag{5}$$

where η is the energy efficiency, $E_f$is the energy used to metal forming work, E_c is the charging energy of the capacitor bank.

With the analytical method described above, the energy efficiency of both pressure distributions in double-direction pressure distributions is further calculated.

As shown in Fig. 6, the energy efficiency of the metal forming work in comparison to a total charged electrical energy of 5 kJ could reach 0.025 for the forming part on the top of the foil specimen in the double-direction pressure distribution. At the same time, the single pressure distribution presents an energy efficiency of 0.055 which is larger than the one in the double-direction pressure mode. The double-direction pressure mode results in a division of the total energy into two parts. As a result, the energy efficiency for the metal forming work in one direction in the double-direction pressure mode is lower than that in the single-direction pressure mode.

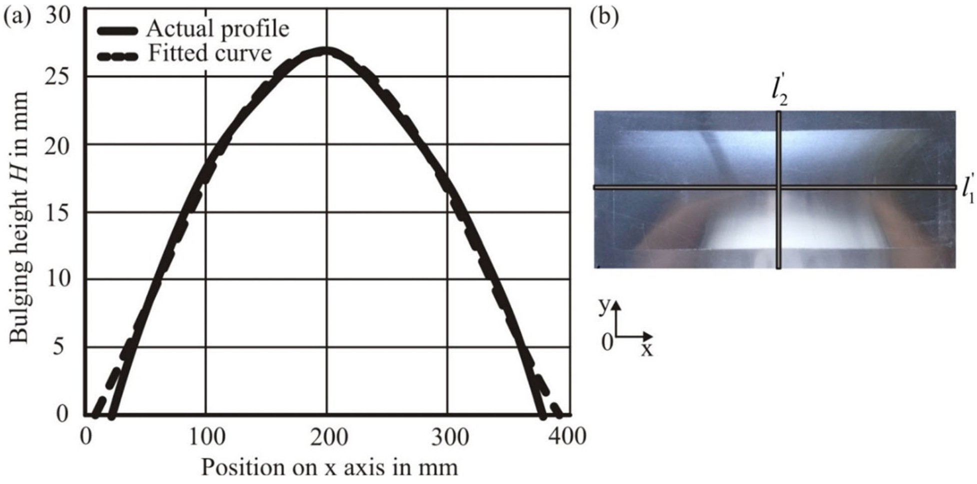


Fig. 4 **a** Actual and fitted curves of the part profile. **b** Forming part in the coordinate system

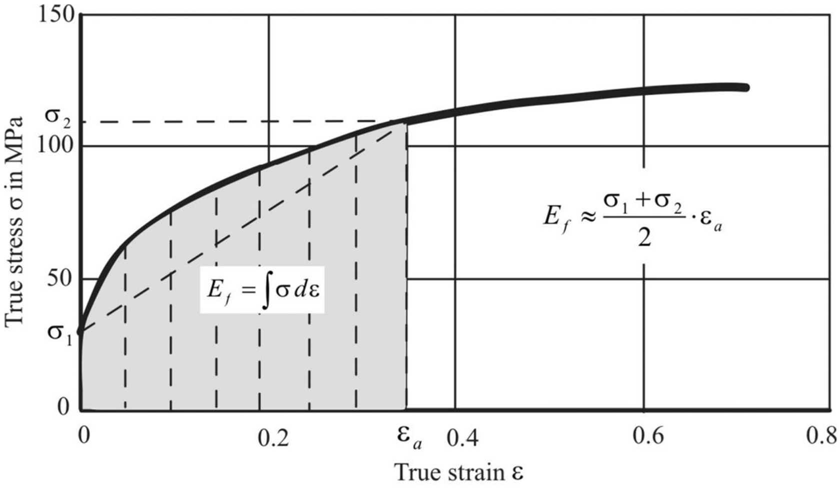


Fig. 5 Calculation of the plastic work

The reason for the difference of the energy efficiency could be attributed to the utilization of the metal gas or plasma during the metal forming process. In the single-direction pressure mode, the induced metal gas or plasma could only travel upwards after the foil vaporization because of the backup plate. But in the double-direction pressure mode, part of the metal gas or plasma could move downwards. Therefore, a considerable amount of the metal gas or plasma are lost in the up-direction and thereafter leads to an attenuation of the pressure as well as a decrease of the metal forming work.

The forming part is assumed to be in a plane strain state. The plastic strain in the direction of the thickness is neglected. Many materials are sensitive to the strain rate during the forming process. This could be reflected in the constitutive model which describes the relation between the stress and strain. In a high-speed forming process, the influence of the strain rate on the forming behavior of the workpiece gets serious because the whole forming process is normally in the range of microseconds. This influence could be described as the hardening effect which improves the flow stress of the workpiece during the deformation. In this study, the quasi-static stress-strain curve is used to calculate the energy efficiency in order to simplify the analysis process. Therefore, the influence of the strain rate on the deformation of the workpiece is not considered. As a result, the calculated energy efficiency in this section should be smaller than the actual value for this process. It should be noted that the polyurethane plate gets deformation during the forming process as well. This deformation could consume some energy for this process. Besides, there are also some other energy losses, for example, the sound and the light generated in the vaporization process. The final energy used for the plastic deformation is only a small part of the initial charging energy of the capacitor bank. Therefore, the energy efficiency in this process is very low. Compared with the conventional forming process, the high-speed forming leads to a relatively low energy efficiency. To improve the energy efficiency is an issue to be solved in the further research for high-speed forming.

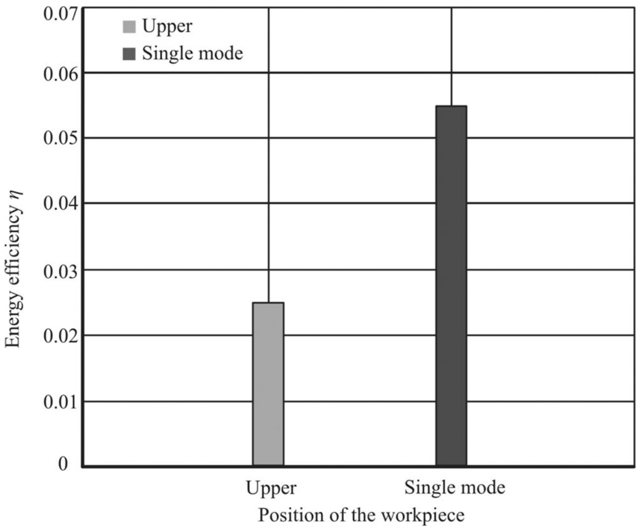


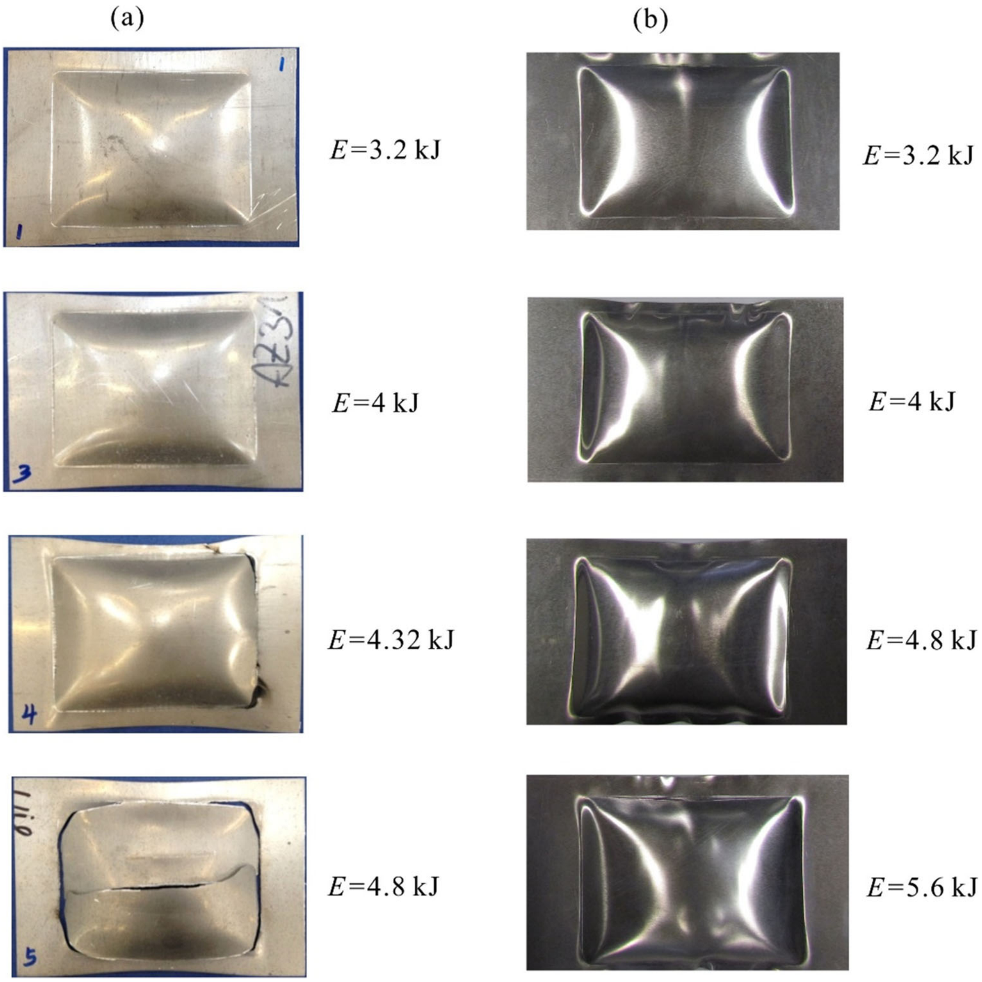
Fig. 6 Calculation of energy efficiency

4 Analysis of the forming behaviors of magnesium alloy

In order to investigate the formability of the magnesium alloy AZ31 at room temperature, the free bulging tests are applied. The initial charging energy of the capacitor bank is varied to different values, for example 3.2 kJ, 4 kJ, and 4.8 kJ. The magnesium alloy and aluminum alloy are formed with the same setup. The achieved forming parts are presented in Fig. 7.

Under a charging energy of 3.2 kJ, the magnesium alloy AZ31 is well formed. There are no cracks occurred on the part. The final bulging part exhibits typical profiles of the free bulging test. Four plastic hinges could be clearly observed on the surface of the part which are the typical features of a

Fig. 7 Free bulging parts. **a** Magnesium alloy AZ31. **b** Aluminum alloy EN AW-6082



rectangular plate under impulsive loading. With the charging energy is increased to 4 kJ, the magnesium alloy AZ31 still shows normal material flow. A forming part with complete profile is obtained. Therefore, the magnesium alloy AZ31 with a thickness of 1 mm could be well formed under a charging energy of 4 kJ. When the charging energy of the capacitor bank is increased to 4.8 kJ, the final bulging part is entirely cracked. The deformation zone is completely separated from the body part and is split into two parts. Therefore, the charging energy of 4.8 kJ is infeasible for the workpiece to be formed in the case of this study. The pressure pulse generated from the foil vaporization is far beyond the forming limit of the magnesium alloy AZ31. As the charging energy of the capacitor bank is adjusted to a smaller value of 4.32 kJ, the final forming part still acquires cracks at the corners. Hence, this charging energy exceeds still the forming limit of the magnesium alloy. Compared with the forming result under the charging energy of 4.8 kJ, there are only two small cracks at the corners. This could be an evidence of the plastic formability of magnesium alloy AZ31 by vaporizing metal foils at room temperature. Under the same process parameters, the aluminum alloy EN AW-6082 exhibits normal material flow and there are no cracks occurred on the parts. This indicates that the applied process parameters are appropriate for the plastic forming of aluminum alloy EN AW-6082. With regard to the metal-forming technique realized by vaporizing foils, the magnesium alloy AZ31 displays relatively poor formability compared to the aluminum alloy EN AW-6082 (Table 2).

Table 2 Chemical compositions of magnesium alloy AZ31 and aluminum alloy EN AW-6082

Magnesium alloy AZ31	Si	Fe	Cu	Mn	Mg	Zn	Al	Be
	0.02	0.005	0.05	0.334	95.451	0.81	3.19	0.1
Aluminum alloy EN AW-6082	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr
	0.7–1.3	0.5	0.1	0.4–1.0	0.6–1.2	0.2	0.1	0.25

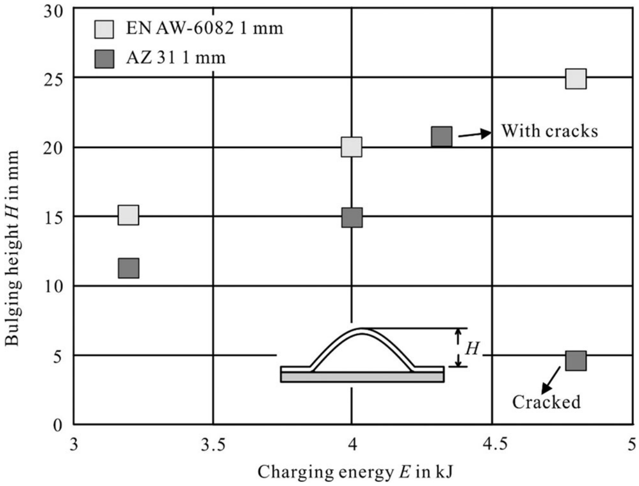


Fig. 8 Bulging height of the forming parts

The final bulging heights of the forming parts by vaporizing metal foils are measured using GOM Atos optical measurement systems and are displayed in Fig. 8. Under a charging energy of 3.2 kJ, the bulging height of the magnesium alloy AZ31 is 12 mm and the aluminum alloy EN AW-6082 is 15 mm. The relative difference in the forming result is 25%. With regard to the charging energy of 4 kJ, the final height of the formed magnesium alloy AZ31 is 15 mm and the height of the aluminum alloy EN AW-6082 is 20 mm. The relative variation in the final height of the parts is about 33.3%. When the charging energy of the capacitor bank is increased to 4.8 kJ, the workpiece of magnesium alloy AZ31 is fractured into pieces. The aluminum sheet metal still acquires normal plastic deformation without cracks and the final bulging height of the formed part is 25 mm. As shown in Fig. 8, the workpiece of magnesium alloy AZ31 is fractured as well. But the deformation zone is not separated from the body part. There are only small cracks at the corner of the part.

Heat treatment is an effective method to strengthen the mechanical properties of magnesium alloys. The mechanical behaviors of the magnesium alloys are strongly affected by the temperature, holding time and heating rate of the heat treatment. In this study, the forming behaviors of the magnesium alloy AZ31 with and without heat treatments are examined. The workpieces of the magnesium alloy AZ31 are prepared by casting and rolling processes. The thickness of the workpieces is 1.8 mm. The forming results of the magnesium alloy AZ31 parts are presented in Fig. 9. The first applied charging energy of the capacitor bank is 4.32 kJ. The reason is that the workpiece of magnesium alloy AZ31 with a thickness of 1 mm obtains small cracks at the corner of the part under a charging energy of 4.32 kJ. This indicates that the charging energy of 4.32 kJ is near to the forming limit of the workpiece of magnesium alloy AZ31 with a thickness of 1 mm. When the thickness of the workpiece of magnesium alloy AZ31 is increased to 1.8 mm, the forming limit of the thickened workpiece is improved and the charging energy of 4.32 kJ could be a suitable energy value for the plastic forming of the magnesium workpiece. As displayed in Fig. 9, the workpiece of magnesium alloy AZ31 with heat treatment acquires normal plastic deformation and is not fractured. This is also the case of the workpiece of magnesium alloy AZ31 without heat treatment. With regard to the deformation amount of these two kinds of workpieces, the magnesium alloy AZ31 without heat treatment obtains larger plastic deformation. When the charging energy of the capacitor bank is increased to 4.8 kJ, the formed part of the magnesium alloy AZ31 with heat treatment is fractured and the deformation zone of the part is cracked into pieces. This indicates that the pressure pulse generated from this charging energy is far beyond the forming limit of the workpiece with heat treatment. But the formed part of magnesium alloy AZ31 without heat treatment acquires larger plastic deformation and there are no cracks occurred on the part, which means that the same pressure pulse is still within the

Fig. 9 Forming parts of magnesium alloy ZA31. **a** AZ31 alloy with heat treatment. **b** AZ31 alloy without heat treatment

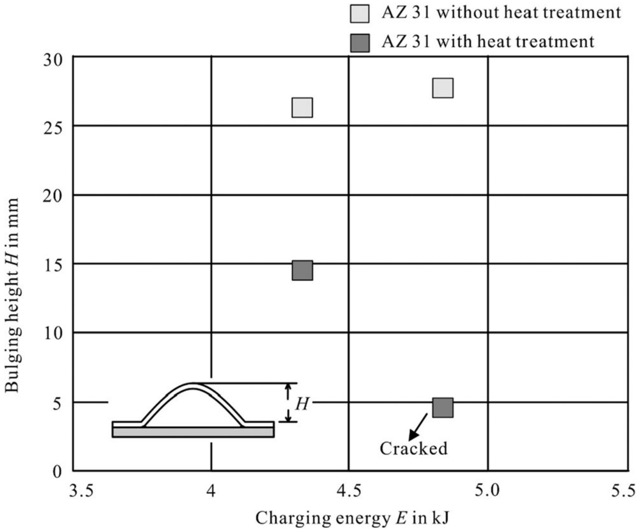


Fig. 10 Bulging height of the forming parts

forming limit of the workpiece without heat treatment. The final bulging heights of the forming part are measured as shown in Fig. 10. The bulging height of the workpiece of magnesium alloy AZ31 with heat treatment is 14 mm under the charging energy of 4.32 kJ, while the final height of the workpiece without heat treatment is 26 mm. As the charging energy is increased to 4.8 kJ, the magnesium sheet with heat treatment is fractured. But the magnesium sheet without heat treatment could continue the plastic deformation without cracks.

With the increase of the charging energy of the capacitor bank, more electrical energy could be deposited into the foil specimen. Hence, the generated metal gas or plasma could be in more active state. Due to the fast impact between the metal gas or plasma and the polyurethane plate, the shock wave could induce stronger pressure pulse for sheet metal forming. The forming limit could be improved with the increase of the thickness of the workpiece. The relative difference in forming behaviors between magnesium alloy AZ31 and aluminum alloy EN AW-6082 is about from 25 to 35% using the metal forming technique of vaporizing foils. The magnesium alloy AZ31 is well formed at room temperature by vaporizing metal foils. A bulging height 25 mm of the forming part could be achieved. With the adjustment of the process parameters, a larger forming depth of the final part is possible as well. Heat treatment could improve the strength of the magnesium alloy AZ31, but reduce its plasticity and thereafter the forming limit of the part. Hence, it is feasible to conduct cold forming process of magnesium alloy AZ31 at room temperature through vaporizing metal foils.

5 Conclusions

This study introduces a simple analytical model to calculate the energy efficiency of the sheet metal forming process by vaporizing metal foils. The forming behaviors of magnesium alloy AZ31 is examined by this forming method. A sheet part with a forming depth of 25 mm is successfully manufactured. It is feasible to carry on sheet forming processes of magnesium alloy AZ31 at room temperature by vaporizing metal foils. Therefore, vaporizing foils is a potential alternative to conduct cold forming processes of magnesium alloy and be applied in industry to manufacture products made of magnesium alloys. Further research on this manufacturing technology could develop effective FEM methods to investigate the forming mechanism of magnesium alloys and identify the influences of different process parameters.

Authors' contributions Sheng Cai and Qinglin Li designed the study, performed the research, analyzed data, and wrote the paper. All authors read and approved the final manuscript.

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Declarations

Ethical approval Yes

Consent to participate Yes

Consent for publication Yes

Competing interests No

References

1. Psyk V, Risch D, Kinsey BL, Tekkaya AE, Kleiner M (2011) Electromagnetic forming-a review. J Mater Process Technol 211: 787–829
2. Davies R, Austin ER (1970) Developments in high speed metal forming. The Machinery Publishing Co.Ltd
3. Vivek A, Brune RC, Hansen SR, Daehn GS (2014) Vaporizing foil actuator used for impulse forming and embossing of titanium and aluminum alloys. J Mater Process Technol 214:865–875
4. Vivek A, Taber GA, Johnson JR, Woodward ST, Daehn GS (2013) Electrically driven plasma via vaporization of metallic conductors: a tool for impulse metal working. J Mater Process Technol 213: 1311–1326
5. Vivek A, Hansen SR, Liu BC, Daehn GS (2013) Vaporizing foil actuator: a tool for collision welding. J Mater Process Technol 213: 2304–2311
6. Vivek A, Presley M, Flores KM, Hutchinson NH, Daehn GS (2015) Solid state impact welding of BMG and copper by vaporizing foil actuator welding. Mater Sci Eng A 634:14–19
7. Cai S, Weddeling C, Tekkaya AE Investigation of tailored pressure distributions by vaporizing tailored foils. Proceedings of the 6th International Conference on High Speed Forming 2014, pp. 229–236.

8. Cai S (2018) Tailored pressure distributions generated by vaporizing tailored foils. Int J Adv Manuf Technol 94:2791–2801
9. Cai S (2017) Double-direction pressure distributions generated by vaporizing metal foils. ASME J Manuf Sci Eng 139:031006–031006-7
10. Cai S (2018) Pressure distributions generated by vaporizing metal foils. Trans Nonferrous Metals Soc China 28:2062–2074
11. Zhang SH, Wang ZT, Zheng L, Zhou LX, Palumbo G (2008) Development of warm sheet forming of magnesium alloys. Proceedings of the 9th International Conference on Technology of Plasticity, pp. 1603-1616.
12. Wang ZM, Gu RY, Chen SC, Wang WR, Wei XC (2018) Effect of upper-die temperature on the formability of AZ31B magnesium alloy sheet in stamping. J Mater Process Technol 257:180–190
13. Li ZH, Zhou GW, Li DY, Jain MK, Peng YH, Wu PD (2020) Forming limits of magnesium alloy AZ31B sheet at elevated temperatures. Int J Plast 135:102822
14. Bergea F, Krügera L, Ullrich C (2014) Forming limit diagrams of twin-roll cast, rolled and heat-treatedAZ31 as a function of temperature and loading rate. Mater Sci Eng A 614:27–35
15. Cai S (2015) Tailored and double-direction pressure distributions for vaporizing-foil forming. Doctoral dissertation, TU Dortmond