Investigation on deformation of DP600 steel sheets in electric-pulse triggered energetic materials forming

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Abstract
Electric-pulse triggered energetic materials forming (ETEF) is a high-speed manufacturing process, which utilizes the chemical energy released by energetic materials (EMs) triggered by underwater wire discharge to plastically shape metals. ETEF is not fully understood, particularly in research on the discharge characteristics of energetic materials triggered by metal wires and the deformation process of metal sheets. The above two problems were investigated in this paper using experimentation and numerical simulation. For the pulse discharge characteristics, the peak values of voltage and current were reduced during the triggering process of energetic materials, and the triggering energy consumption of energetic materials was quantified to be about 200 J. The matching parameters of different capacitor-voltage devices may be insensitive to triggering the energy release of energetic materials. The maximum major strain and thinning rate of the bulged specimen under ETEF conditions were significantly reduced when compared to the quasi-static specimen with the same bulging height, and the specimen's deformation uniformity and strain distribution were improved. The simulation results showed that the addition of energetic materials significantly improved the plastic strain energy of the blank. The deformation of the blank in ETEF can be divided into two stages: the initial chemical energy action stage and the inertia action stage. The bulging height of sheet metal increased by nearly 301% in inertia action stage, accounting for 80% of the total deformation time, and the effective plastic strain distribution was more uniform.

Keywords High-velocity forming · Energetic materials · Pulse discharge characteristics · Numerical simulation · Plastic strain energy

1 Introduction

To improve the fuel efficiency and crashworthiness of automobiles, the use of high-strength steel to develop lighter and safer cars has become a trend in the automobile industry. Advanced high-strength steel sheets have been widely used in the production of impact-resistant and energy-absorbing components. However, the use of advanced high-strength steel in auto-body components is still limited to simply shaping automobile parts due to its poor formability, which makes it difficult to use in traditional deep drawing processes for complicated auto parts. To improve its strength and formability even more, a suitable forming process must be chosen. Compared with traditional forming processes, high-velocity forming (such as electromagnetic forming and electrohydraulic forming) is very effective in improving the strength and formability of materials, so many researchers have conducted research. At high strain rates, the flow stress of many materials increases significantly with the increase of strain rate [1–4], showing strain rate sensitivity. According to Psyk et al. [5], the workpiece is accelerated to a velocity of up to several hundred m/s and strain rates of \(10^{3}/s\) in the EMF process, thereby improving the formability and strength of the material, which will help enhance the crashworthiness of automotive parts.

Electromagnetic forming is a method that uses Lorentz force generated by pulsed magnetic field to deform workpiece at high speed [6, 7]. Therefore, this non-contact feature

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of electromagnetic forming can significantly improve the surface morphology of the workpiece [8]. However, in practical applications, the forming capability of EMF is typically limited by the insulation strength and mechanical strength of the coil and the energy storage of the electric pulse generator. Increased discharge energy increases Lorentz force, but it also causes insulation breakdown and coil breakage, affecting forming results and potentially damaging experimental equipment. Electrohydraulic forming is a high-velocity forming technology in which shock waves generated by the discharge of two electrodes in a liquid medium cause the workpiece to deform plastically [9]. Water is used as a “punch” to form workpieces in electrohydraulic forming, which allows for a lot of process flexibility. Additionally, electrohydraulic forming is also more widely used than electromagnetic forming because it is not limited by material conductivity. For instance, Golovashchenko et al. [10] and Tang et al. [11] successfully applied electrohydraulic forming to trimming of advanced high-strength steel. Mamutov et al. [12] used electrohydraulic forming to manufacture a complex geometry automotive part. However, the energy utilization efficiency is extremely low due to the underwater electrode discharge, and even if the wire between the two electrodes is discharged, its energy utilization efficiency is only 24%, as concluded by Efimov et al. [13]. As a result, there will be a waste of energy.

Based on the aforementioned issues, Yu et al. [14] proposed ETEF, a new high-velocity forming method that uses underwater metal wire electric explosion to ignite the chemical energy released by energetic materials to complete the workpiece’s deformation. Experiments revealed that energetic materials had a high energy effect, and the energy level of energetic materials was quantified as 3.04 kJ/g. The discharge characteristics of underwater wire electric explosion have been studied by researchers. Han et al. [15] studied the underwater electrical explosion of copper wires and found that the deposited energy influenced the expansion of the discharge plasma channel and affected the shock wave characteristics. Grinenko et al. [16] conducted an experimental study on the underwater electric explosion of copper wire and discovered that the efficiency of electrical energy deposition into the mechanical energy for the fluid flow was 25% and the maximum pressure obtained at the boundary of discharge plasma channel was around 600 MPa. Therefore, the metal wire in ETEF ignites the surrounding energetic materials to release energy similar to explosive forming (EF). Traditional EF explosives have high-energy effect, which can reduce the production cost of small-batch formed parts, and are widely used in manufacturing low-volume formed parts, such as manufacturing thin-walled decorating spheres for city construction and art works of copper plate relief [17, 18]. However, the research on the discharge characteristics of energetic materials triggered by metal wires and the energy release level of energetic materials under different capacitance–voltage matching parameters is unclear, and the deformation process of workpieces in ETEF is not perfect. Therefore, it is necessary to conduct a comprehensive study of the above contents.

A better understanding of the discharge characteristics of energetic materials triggered by metal wires, as well as the dynamic deformation process of the ETEF sheets, would aid in the implementation of this forming process in the automotive industry. As a result, the discharge characteristics of energetic materials triggered by metal wires under different capacitance–voltage matching parameters, as well as the influence of energetic material energy release level on sheet bulging, were investigated in this work. Experiment and numerical analysis were used to investigate the deformation process of DP600 steel sheet in ETEF, such as strain distribution characteristics, deformation uniformity, and dynamic deformation process.

## 2 Experimental procedures

### 2.1 Material description

The as-received material was cold-rolled DP600 steel sheet with a thickness of 0.8 mm and provided by Baoshan Iron & Steel Co., China. Table 1 shows the quasi-static tensile mechanical properties and main chemical compositions (wt%) of this material.

The new energetic materials selected in this study were aluminum (Al) particles and ammonium perchlorate (AP) particles. Al is a smooth sphere with an average particle size of 1–3 μm, and agglomeration occurs because of the small size of Al. AP particles showed irregular spheres with an average particle size of 140 μm. Physical mixing was used to create the energetic materials used in this experiment, Al/ AP (10 wt% Al, 90 wt% AP).

### 2.2 Energy release during ETEF

The process of instantaneous melting and vaporization of metal wires to form plasma under high-voltage pulsed current is referred to as electrical explosion of metal wires. Plasma is heated and expanded by intense Joule heating, resulting in the formation of a plasma channel filled with high pressure and heat. Strong shock waves are radiated during plasma diffusion, which are quickly converted into sound pressure pulses and then spread to the surrounding medium, as described by Timoshkin et al. [19]. The ETEF method ignited energetic materials and released energy in water by using an electric explosion of metal wire to form plasma. The energy release process of plasma-triggered energetic materials can be divided into three stages: heating, ignition, and detonation (Fig. 1).

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Energetic materials react chemically and release high energy after ignition, described as heat and shock waves by Pagoria et al. [20]. Heat and shock waves locally heat up inside energetic materials to form “hot spots,” causing the entire energetic material to release energy quickly [21]. Energetic materials are characterized by high energy, a wide pulse, and a strong shock wave during energy release. Thus, they are widely used for infrared pulse radiation, fossil energy extraction, and rocket propulsion.

### 2.3 Experimental setup for free bulging tests

To investigate the deformation of a DP600 steel sheet (with a diameter of 220 mm) under a biaxial stress state, free bulging tests were performed. The schematic of experimental setups for bulging tests are illustrated in Fig. 2. DP600 steel sheet was deformed in the ETEF process by discharging metal wire with an electric pulse generator, instantly igniting energetic materials, releasing chemical energy, and generating a shock wave in a liquid chamber (Fig. 2a). The Rogowski current waveform transducer (Power Electronic Measurements Ltd, Nottingham, UK) and the P6015A high voltage probe (Tektronix, USA) were used to measure the current and voltage generated by the electric pulse generator discharging the metal wire, respectively. Energetic materials were placed in a 40-mm-long EMs cylinder. The top die was an open with an inner diameter of 100 mm and an entry radius of 10 mm. Figure 2b shows the displacement variation with time during the sheet bulging process measured by position sensitive detector (PSD), namely a Laser Sensor M70LL (MEL Mikroelektronik GmbH, Germany). As shown in Fig. 2c, it was quasi-static forming (QSF) and quasi-static hydraulic forming (QSHF). The diameter of the punch was 100 mm, and the filet radius of the bottom die opening was 10 mm. The punch was replaced by high-pressure liquid for QSHF. The plastic strain distribution of the deformed specimen was measured using an optical three-dimensional (3D) deformation measuring system ARGUS-V6.3.1 (GOM GmbH, Germany). First, an electrochemical etching was used to create circular array grids with a diameter of 1 mm and an adjacent center distance of 2 mm on the surface of the initial specimens. A GOM system was then used to calculate the strain data of the deformed grids.

### 2.4 Capacitance–voltage matching parameter tests

The energetic materials in ETEF are triggered by plasma generated by wire explosion to release energy. Therefore, the effect of capacitance–voltage matching parameters in various electric pulse generators (EPG) on the variation characteristics of current and voltage after discharge, as well as the energy release of energetic materials, must be thoroughly investigated. Table 2 lists the discharge parameters of different electric pulse generators and the quality of ignited energetic materials. The relationship between discharge energy $E$, equipment capacitance $C_i$, and discharge voltage $U$ can be expressed as:

$$E = \frac{1}{2}C_i \cdot U^2$$  \hspace{1cm} (1)

At the same discharge energy (1.37 kJ), the discharge test of the same energetic materials (2 g) triggered by different electric pulse generators was carried out. The effect of equipment parameters on the changes in current and voltage waveforms following the underwater discharge of pure metal wire and the discharge of energetic materials triggered by metal wire was investigated. The current and voltage waveform data were obtained using a Rogowski current waveform transducer and a Tektronix P6015A high

### Table 1 Mechanical properties and chemical composition of the DP600 steel sheets

| Yield strength/MPa | Tensile strength/MPa | Total elongation (engineering strain, %) | Uniform elongation (engineering strain, %) | Chemical composition wt (%) |
|-------------------|---------------------|----------------------------------------|------------------------------------------|-----------------------------|
| 384.6             | 658.7               | 26.63                                  | 16.33                                    | Mn                           |
|                   |                     |                                        |                                           | Si                           |
|                   |                     |                                        |                                           | Ni                           |
|                   |                     |                                        |                                           | Cr                           |
|                   |                     |                                        |                                           | Cu                           |
|                   |                     |                                        |                                           | Al                           |
|                   |                     |                                        |                                           | Fe                           |
|                   |                     |                                        |                                           | 1.75                         |
|                   |                     |                                        |                                           | 0.02                         |
|                   |                     |                                        |                                           | 0.11                         |
|                   |                     |                                        |                                           | 0.28                         |
|                   |                     |                                        |                                           | 0.57                         |
|                   |                     |                                        |                                           | 1.41                         |
|                   |                     |                                        |                                           | 95.83                        |

(I) Heating stage: The temperature of solid energetic materials is rapidly heated from the initial temperature $T_0$ to the decomposition temperature $T_d$ by heat conduction of high temperature plasma. During the process, no chemical reactions occur.

(II) Ignition stage: As plasma continues to diffuse, the temperature of energetic materials rises from $T_d$ to $T_s$ (the burning surface temperature) and ignites. At this stage, energetic materials go through a phase transition from solid to liquid and then to vapor, producing high-temperature and high-pressure gas products on the surface.

(III) Detonation stage: As energetic materials surrounding the metal wire ignite, the gas temperature in stage II rapidly rises from $T_s$ to $T_f$, and more energetic materials are ignited to release energy. Energetic materials decompose rapidly within a brief period to produce more gases. These gases expand quickly within a limited space, evolve into shock waves, and compress surrounding media to complete detonation.
voltage probe, respectively, and the waveform results were displayed using an oscilloscope (Fig. 2a).

To study the influence of capacitance–voltage matching parameters in EPG on energy release of energetic materials, we used different equipment parameters to conduct discharge tests on energetic materials, which were evaluated by the final bulge height, deformation speed, and effective plastic strain of the specimens during ETEF. The acquisition parameters were set as follows: displacement range, 0–50 mm; sensitivity reached 0.4 V/mm; and acquisition frequency, 500 KHZ. The effective plastic strain of the deformed specimens was measured by the ARGUS-V6.3.1 testing system.

3 Results and discussion

3.1 Influence of capacitance–voltage matching parameters on discharge characteristics

The effect of capacitance–voltage matching parameters on the discharge characteristics of metal wires and its triggering energetic materials is a critical link in the study of energetic materials energy release during the ETEF process. A metal wire (molybdenum wire with a diameter of 0.2 mm and a length of 45 mm) and an EMs cylinder were used as the discharge object under different equipment parameters (EPG-A, EPG-B), and the discharge voltage $U(t)$ and current $I(t)$ were obtained, as shown in Fig. 3a–b. According to Eqs. (2) and (3), the waveforms of instantaneous power $P_t$ and the deposited energy $W_t$ were calculated respectively (Fig. 3c–d).

$$P_t = I(t) \cdot U(t)$$  \hspace{1cm} (2)

$$W_t = \int_0^t I(t) \cdot U(t) \, dt$$  \hspace{1cm} (3)

According to the current and voltage curves presented in Fig. 3a, b, at the same electrical pulse generator parameters, the addition of energetic materials resulted in a decrease in the maximum voltage of the wire before breakdown, and the peak value of current waveform decreased significantly after breakdown discharge. Generally, wire explosion will undergo a series of physical changes, that is, the phase transition from solid, liquid, gas to plasma. The physical process changed after the energetic materials were added, and the plasma formed by wire explosion heated and ignited energetic materials for chemical reaction. In this process, the ignition of energetic materials occurred at the peak of voltage, which reduced the peak of current compared with the Mo wire explosion in water, indicating that the electrical conductivity changed during the ignition of energetic materials by metal wires. There are two possible explanations for
this phenomenon. One is that energetic materials are ignited, and the other is that after wire explosion forms plasma, the nearby energetic materials are heated by thermal radiation to form a conductive layer, and the extra conductive layer (gas products produced by vaporization of energetic materials) increases the resistance of the discharge channel [22]. Both of these factors can reduce conductivity between electrodes and thus reduce current in the circuit. Furthermore, the introduction of energetic materials reduced the maximum electric power and the electric energy deposited in the discharge channel, as calculated by Eqs. (2) and (3). This phenomenon could be explained by the use of some energetic materials with high temperatures as extra conductive substances, which accelerates the breakdown process of the wire vaporization discharge channel, resulting in a decrease in deposition energy. According to Fig. 3, the energy consumed during the ignition of energetic materials was approximately 200 J, implying that energetic materials were ignited during the wire explosion, followed by chemical reactions and shock waves. Although energetic materials consumed plasma energy during the ignition process, the addition of energetic materials provided an additional shock wave amplitude, namely the secondary shock wave peak effect, which increased the impulse of the entire system, as demonstrated by Zhou et al. [23]. According to our previous studies [14], compared with pure electrohydraulic forming (discharge voltage 3 kV), the bulging height of sheet

### Table 2

| Electric pulse generator | Rated capacitance, $C_r$ (μF) | Discharge energy, $E$ (kJ) | Discharge voltage, $U$ (kV) | EMs, mass (g)  |
|-------------------------|-------------------------------|--------------------------|-----------------------------|----------------|
| EPG-A                   | 304                           | 1.37                     | 3.0                         | 2.0 g          |
| EPG-B                   | 100                           | 1.37                     | 5.23                        | 2.0 g          |

![Fig. 2](image-url)  
Schematic of experimental setup under free bulging tests: (a) ETEF, (b) Laser-Sensor M70LL, and (c) QSF/QSHF
metal under ETEF condition (3 kV/2 g) increased by 162%, indicating that the shock wave energy produced by energetic materials is the primary reason for the significant increase in sheet metal bulging height.

### 3.2 Influence of capacitance–voltage matching parameters on sheet bulging

In this section, the influence of energy release from energetic materials triggered by metal wire on sheet bulging is discussed under the matching parameters of capacitance–voltage of electric pulse generator. Figure 4 presents the changing process of sheet metal bulging height and deformation speed over time under various equipment parameters. The specimen was rapidly deformed in a short period of time, as evidenced by the final bulging height of approximately 34 mm. Under different equipment parameters, the speed of the apex (point A) of the bulged specimen changed with time as follows: the speed of the sheet reached the maximum at about 20 μs, then dropped rapidly,
and then rose slightly to maintain high speed movement, and the deformation speed was close to zero at about 300 μs, finally until the end of deformation. Therefore, under different capacitance–voltage matching equipment parameters, the apex velocity of bulged sheet has the same trend with time in ETEF process. Additionally, according to our previous research [14], the variation trend of the peak velocity of the specimen obtained in ETEF numerical simulation under the parameter of 3 kV/2.0 g was in good agreement with the experimental results (Fig. 4a). Figure 5 shows the bulged specimen and effective plastic strain under different equipment parameters. In the deformation zone of φ100mm, the distribution trend of effective plastic strain of the sheets under EPG-A and EPG-B equipment was similar, and the maximum effective plastic strain values were 49.3% and 50.4%, respectively. Table 3 lists the final bulging height, maximum deformation speed, and maximum effective plastic strain obtained on the sheet under different equipment parameters, and their values are at the same level.

According to the deposition energy curves in Sect. 3.1 (Fig. 3c, d), the deposition energy consumed by the ignition of energetic materials by metal wires was about 200 J under different capacitance and voltage matching parameters. Based on our previous studies [14], the chemical energy per gram of energetic materials was 3.04 kJ. Using the parameters of EPG-A equipment as an example, in the energy system of 3.0 kV/2.0 g, the energy deposited after the wire triggered the energetic materials was 1.07 kJ. Consequently, the energy released by the energetic materials accounted for 86% of the total energy system, indicating that the chemical energy released by energetic materials was primarily responsible for the sheet’s bulging height. The bulging results obtained under different equipment parameters were essentially consistent in terms of final bulging height, velocity variation trend, and effective plastic strain value. Therefore, the initial energy storage of electric pulse generators plays a role in triggering energetic materials to release energy, and the capacitance–voltage matching parameters of different electric pulse generators may have no effect on the energy level released by energetic materials. In other words, energetic materials were insensitive to the initial equipment conditions of the electrical pulse generator and had low requirements for the matching parameters of the equipment’s capacitance–voltage. The electric pulse generator can provide enough system triggering energy, which can trigger energetic materials to release energy stably, thereby increasing the flexibility of initial equipment condition triggering. This will be beneficial to the popularization and application of ETEF. Subsequently, we select EPG-A equipment parameters to study the deformation of the sheet under ETEF in detail.

### 3.3 Analysis of deformation results of sheet metal

The bulging height, maximum strain value, and maximum thinning rate of the bulged specimen during ETEF were used to analyze the deformation of DP600 sheet, as shown in Table 4. Figure 6 shows the specimens and profiles obtained from ETEF, QSF, and QSHF tests with the same bulging height. It can be seen that the non-uniform deformation of the QSF specimens occurred in the deformation zone 20–40 mm from the apex of the sheet. The deformation of the specimen obtained by QSHF was more uniform than that of QSF. Likewise, compared with QSF, the profile of the specimen under ETEF condition was more uniform. When the energetic materials were triggered to release energy by the metal wire, it pressed the surrounding water medium to obtain kinetic energy and pushed the sheet to complete high-speed deformation. The water medium has a certain fluidity as a flexible “punch”, which improves the specimen’s profile uniformity. The thickness distribution is an important index for determining the deformation uniformity of deformed specimen. Figure 7 shows the thickness distribution of the bulged specimens. In the deformation zone of φ100mm, the thickness distribution of the specimens under ETEF condition was relatively uniform, and the maximum

| Table 3 Deformation results of sheets in ETEF under different equipment parameters |
|---------------------------------------------------------------|
| Electric pulse generator | ETFE Height, H (mm) | Max velocity, V (m/s) | Effective plastic strain, (%) |
|--------------------------|---------------------|----------------------|-------------------------------|
| EPG-A 3.0 kV + 2.0 g     | 34.0                | 255                  | 49.3                          |
| EPG-B 5.23 kV + 2.0 g    | 34.5                | 252                  | 50.4                          |
The thinning rate occurred in the apex area of the specimens, which was 15.3% (specimen NO.1) and 23.8% (specimen NO.2), respectively. Under the QSF condition, the thickness distribution of the specimens was deformed unevenly in the deformation zone, resulting in a severe thickness reduction, with the maximum values of 22.1% (specimen NO.3) and 27.6% (specimen NO.4), respectively. Additionally, the thickness reduction area of QSHF was concentrated in the central area of the specimen, and the thinning was severe, with the maximum thinning rate of 31.4%. Therefore, compared with the quasi-static bulged specimens with the same bulging height (24 mm, 29 mm), the maximum thickness rate of the specimens under the conditions of ETEF/3.0 kV/1.0 g and ETEF/3.0 kV/1.5 g was reduced by 30.8% and 13.8%, respectively.

According to Table 4, the maximum major strain and the maximum thinning rate of the specimens obtained under ETEF were lower than those of quasi-static conditions, which inevitably affected the strain distribution in the deformation zone of the specimens. Figure 8 exhibits the strain distribution and thinning rate of ETEF/1.5 g, QSF/29 mm, and QSHF/29 mm specimens with the same bulging height. The maximum major strain and the maximum minor strain of the specimen under the QSF condition were located 20 mm from the apex of the sheet, and their values were 21.6% and 13.7%, respectively, and distributed symmetrically. Under QSHF condition, the maximum major strain and the maximum minor strain of the specimen were located at the apex of the sheet, and their values were 20.9% and 19.6%, respectively, resulting in severe strain concentration. Clearly, the maximum strain obtained by ETEF was distributed at the apex of the specimen, and its maximum major strain and maximum minor strain were 15.2% and 14.2%, respectively (Fig. 8a).

Table 4 Summary of the ETEF, QSF, and QSHF test results

| Specimen number | Type   | Voltage (kV) | Energy (kJ) | EMs, mass (g) | Dome height (mm) | Maximum strain (%) | Major strain | Minor strain | Thinning rate |
|-----------------|--------|--------------|-------------|---------------|------------------|--------------------|--------------|--------------|---------------|
| NO. 1           | ETEF   | 3.0          | 1.368       | 1.0           | 24               | 9.24               | 8.16         | 15.3         |
| NO. 2           | ETEF   | 3.0          | 1.368       | 1.5           | 29               | 15.2               | 14.2         | 23.8         |
| NO. 3           | QSF    | -            | -           | -             | 24               | 16.7               | 12.1         | 22.1         |
| NO. 4           | QSF    | -            | -           | -             | 29               | 21.6               | 13.7         | 27.6         |
| NO. 5           | QSHF   | -            | -           | -             | 29               | 20.9               | 19.6         | 31.4         |

Fig. 6 The specimens and profiles obtained from ETEF, QSF, and QSHF tests with the same bulging height (24 mm, 29 mm)
60 mm deformation zone, the strain in two principal in-plane directions was almost equiaxial, and the strain distribution was obviously improved. The maximum major strains were 29.6% and 27.3% lower than that of QSF and QSHF, respectively. Moreover, the thinning rate also showed similar distribution characteristics, and the thinning rate of the specimen under ETEF conditions was significantly reduced compared with that of quasi-static conditions (Fig. 8b). According to our previous tests [14], the specimen also cracked here under quasi-static conditions, mainly because the contact friction between the specimen and punch increased in the deformation zone, which resulted in a large deformation and serious thickness thinning in this zone [24]. Therefore, the maximum strain and thinning rate of ETEF specimens decreased, which significantly improved the uniformity of strain distribution in the deformation zone.

3.4 Dynamic deformation process of sheet metal

LS-DYNA simulation software was adopted to simulate the dynamic deformation process of the sheet in ETEF. A quarter geometric model (including Mo wire, EMs, water, air, blank, blank holder, and liquid chamber) was established based on the test tooling in Fig. 2a. Then, the energy input into ETEF was preset, including the electrical energy input by metal wire (Fig. 3c) and the chemical energy of energetic materials. The former was the electric energy predetermined by the metal wire via the electric pulse generator, which primarily served the purpose of igniting energetic materials; the latter was the energy released by the chemical reaction of energetic materials after they had been ignited by metal wire. The chemical energy released by energetic materials was primarily responsible for the sheet’s deformation. Our previous work [14] contains a detailed implementation process of ETEF numerical simulation.

According to the description in Sect. 2.2, energetic materials mainly produce heat energy, light energy, and mechanical energy after releasing energy and form shock waves to work on the surrounding water medium, resulting in plastic deformation of the workpiece. Therefore, the plastic strain energy was used to evaluate the contribution of energy released by energetic materials to the plastic deformation of the blank [25]. Figure 9 shows the change in plastic strain energy of the blank over time following energy release by energetic materials in the ETEF process. It was discovered that the addition of energetic materials significantly increased the plastic strain energy of the blank. Compared with the final plastic strain energy of EHF/3 kV, the plastic strain energy obtained under the conditions of ETEF/3 kV/1.0 g and ETEF/3 kV/1.5 g contributed 60% and 74% to the plastic deformation of the blank, respectively. Specifically, according to the research in Sects. 3.1 and 3.2, it was found that the deposition energy consumed by energetic materials during ignition was about 200 J, which was relatively small in the whole energy system and even negligible, but it reduced the deposition energy under EHF/3 kV conditions. Therefore, the plastic strain energy obtained under the conditions of ETEF/3 kV/1.0 g and ETEF/3 kV/1.5 g contributed slightly more than 60% and 74% to the plastic deformation of the blank, respectively. As a result, the energy released by energetic materials during the ETEF process played a significant role in the blank’s plastic deformation. Furthermore, the changing trend of the blank’s plastic strain energy shows that the increase in plastic strain energy can be divided into two stages. Using ETEF/3 kV/1.5 g as an example, the plastic strain energy increased slightly within 60 μs, and the plastic strain energy of the blank increased significantly in 60–300 μs. Therefore, after the energetic materials released energy, the shock wave pressure and the stress and strain on the blank must change.
significantly in different stages of plastic deformation. Hence, we take the ETEF/1.5 g parameter as an example for subsequent numerical simulation analysis.

Figure 10 exhibits the change of the shock wave pressure generated by the elements on the metal wire and energetic materials with time during the ETEF process. Elements A, B, and C were on metal wire, and elements D, E, and F were on energetic materials. After the electric pulse generator discharged, the shock wave pressure of the elements on the metal wire and energetic materials were generated almost simultaneously, and the duration from the generation of the pressure to the rapid drop were about 10 μs. Remarkably, from the peak pressure on the elements, it can be found that the maximum value of the shock wave pressure generated by the elements on the energetic materials was greater than that on the metal wire, indicating that the energetic materials were ignited by the metal wire and increased the peak value of the shock wave. Therefore, according to the analysis in Sect. 3.1, the addition of energetic materials increased the total energy of the system, that is, increased the pressure of shock wave, which is consistent with the conclusion of Zhou et al. [23]. After 10 μs, the pressure on the elements decreased slowly, reaching only 8 MPa at 50 μs and close to zero at 60 μs. Therefore, the total duration of the electrical energy of metal wire and the chemical energy generated by energetic materials was 60 μs.

Figure 11 presents the result velocity and effective stress of the elements on the sheet over time. First, the metal wire and energetic materials released energy within 0–60 μs. At 24 μs, the shock wave pressure was transmitted to the sheet, which caused the effective stress on the sheet to increase rapidly, and the speed of the element L rapidly increased to the maximum value of 188 m/s. Following that, due to the weakening of the initial electrical and chemical energy within 24–60 μs, the deformation speed of the sheet decreased. However, the effective stress on the sheet continued to increase, and the increase became slow at 50 μs, and then after 60 μs, the speed of the sheet increased again under the action of water flow pressure and inertia. Eventually, the effective stress decreased rapidly when it increased to 250 μs, and the deformation speed of the sheet also decreased rapidly at 200 μs, with the deformation ending at 300 μs. Therefore, the deformation process of sheet in ETEF can be divided into two stages: (i) the early stage of deformation (within 0–60 μs) and the initial chemical energy action stage of energetic materials and (ii) the late deformation period (within 60–300 μs) that belongs to inertia action stage.

Figure 12 shows the contours/vector of the bulging height (Y-displacement) of the tested specimen during the ETEF process. In the initial chemical energy action stage of energetic materials, the bulging height of the specimen at 60 μs was only 7.5 mm, presenting a conical bulging profile, as shown in Fig. 12a. At 120 μs, the specimen showed an approximately ellipsoidal bulging profile (Fig. 12b), and the deformation profile was further improved. At 200 and 300 μs, the profile of the bulged specimen was hemispherical, and the bulging height of the final specimen is 30.1 mm, with an error of only 3.8% from the experimental bulging height of 29 mm (Table 4). Therefore, in the inertia action stage (within 60–300 μs), the bulging height of the specimen increased by 301% compared with the initial chemical energy action stage of the energetic materials. The inertia effect accounted for 80% of the total deformation time, which significantly increased the bulging height of the sheet metal and played a leading role in the plastic deformation.

The profile change of the bulging specimen during the ETEF process will inevitably affect the distribution of the effective plastic strain. The variation of the effective plastic strain of the deformed specimen at different times is shown in Fig. 13. At 30 μs, the effective plastic strain with elliptical
annular distribution appeared on the specimen; at 60 μs, the effective plastic strain presented a rectangular distribution in the central deformation zone of the specimen; at this time, the width of the strain concentration zone was parallel and equal to the geometric dimension of EMs cylinder (Fig. 2a). At 100 μs, the effective plastic strain concentration area was approximately elliptical (the ratio of long axis to short axis: 1.6), while the overall effective plastic strain on the blank was elliptical, and the strain distribution was extremely uneven. At 120 μs, the effective plastic strain in the central deformation zone was close to a circle (the ratio of long axis to short axis: 1.1), and the effective plastic strain was significantly improved. Within 200–300 μs, the effective plastic strain in the central deformation zone was uniformly distributed. These results further indicate that the energy released by energetic materials during the ETEF process can significantly improve the distribution of effective plastic strain, which is of great significance for forming axisymmetric parts.
Conclusions

In this research, the technological characteristics of ETEF were revealed from the aspects of pulse discharge characteristics and dynamic deformation process of sheet metal. To achieve this goal, experiments and numerical simulations were carried out. The conclusions of this study can be summarized as follows:

1. In the process of ETEF, due to the addition of energetic materials, the waveform amplitude of discharge voltage and current decreased, and the peak value of current decreased significantly. Furthermore, the electric power and deposition energy generated by various pulse equipment discharges decreased, and the triggering energy consumption of energetic materials was estimated to be around 200 J; the capacitance–voltage matching parameters of various electric pulse generators may be insensitive to the energy release level of energetic materials.

2. Compared with the quasi-static specimen with the same bulging height (29 mm), the maximum major strain and the maximum thinning rate of the bulged specimen under ETEF/3 kV/1.5 g decreased by 29.6% and 13.8%, respectively, which significantly improved the strain distribution, thickness distribution, and deformation uniformity of the sheet.

3. The simulation results showed that the addition of energetic materials significantly improved the plastic strain energy of the blank. Compared with EHF/3 kV, the final plastic strain energy obtained under the conditions of ETEF/3 kV/1.0 g and ETEF/3 kV/1.5 g contributed 60% and 74% to the plastic deformation of the blank, respectively.

4. (i) In the initial chemical energy action stage of energetic materials, the effective stress on the blank increased rapidly, and the maximum speed reached 188 m/s. (ii) In the inertia action stage, the bulging height of the specimen increased by nearly 301%, and the error between the bulging height of numerical simulation and experiment was 3.8%. During ETEF, the effective plastic strain of sheet metal was significantly improved, and inertia effect accounted for 80% of the total deformation time, which played a leading role in plastic deformation.

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Data availability All data generated or analyzed during this study are included in this manuscript.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.
Conflict of interest  The authors declare no competing interests.

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