Numerical investigation on the effects of circuit parameters on the plastic deformation of fastener holes in thin aluminum alloy via electromagnetic expansion process

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Abstract
The size of the plastic deformation zone caused by fastener hole strengthening is a critical indicator of the strengthening performance. In this study, 2A12-T4 aluminum alloy specimens with a hole diameter of 6 mm and thickness of 1.5 mm were strengthened by Lorentz force through the electromagnetic strengthening method. The numerical results show that the Lorentz force can introduce tensile stress in both hoop and radial directions in the specimen during the strengthening process and produce a high compressive hoop residual stress around holes without serious axial deformation compared with the conventional cold hole expansion process. The simulation results are experimentally validated by the grid method in verifying the residual strain, and the fatigue life can be improved by several times after strengthening. Furthermore, under the same discharge energy, there is an optimal capacitance of around 40 μF in this work to achieve the maximum size of the plastic deformation zone. In addition, a larger crowbar resistance can cause a stronger radial inward Lorentz force during the unloading process and result in lower residual stress; therefore, the crowbar resistance should be as small as possible.

Keywords Electromagnetic strengthening · Hole expansion · Dual-coil system · Plastic deformation

1 Introduction

For the purpose of jointing the fasteners in aircraft, automobiles, etc., it’s unavoidable to drill holes in these engineering structures and components. However, cracks are more preferred to occur around holes during cycling loads owing to severe stress concentration issues, which significantly reduce the fatigue life of the fasteners [1]. To improve the durability and reliability of devices, it is important to extend the fatigue life of these fastener holes. Conventional hole strengthening methods, named cold working, such as direct cold expansion [2], split sleeve cold expansion [3–6], and shot peening [7], have already been developed. The principle of these methods is to push the hole wall radially outward by an external load and cause small elastic/plastic deformation. When the external load is removed, the plastic deformation zone (PDZ) would be compressed by the spring back of the surrounding elastic area, thus the compressive residual stress is produced as well as the larger PDZ area, the stronger compressive residual stress [8]. This compressive residual stress can reduce the service tension stress and suppress the initiation of the crack, thus extending the fatigue life of fasteners [9].

The size of the PDZ is an important indicator of strengthening performance. The commonly used hole strengthening methods can produce a more considerable size of PDZ in thick Al fastener holes than in thin ones. To increase the fatigue life of the fastener holes, the most effective way is to appropriately increase the degree of an interference fit, which can introduce a larger size of PDZ [10, 11], a higher compressive residual stress [1, 12, 13] and a longer fatigue life [14]. However, Sanford et al. [11] demonstrated that when the interference fit degree was higher than 5%, the out-of-plane deformation,
ascribed to the pulling of the hardened mandrel, would hinder the further expansion of the PDZ in the radial direction. As for thin fastener holes, Ofsthum [9] found that the cold working method would reduce the fatigue life of Al specimens with a thickness of 1.422 mm since a hole extrusion named “volcano” was formed. Amjad et al. [8] and Poolsuk et al. [10] proposed that the size of PDZ was larger and more axisymmetric in thick fasteners compared with thin ones. These investigations demonstrate that the conventional hole strengthening methods are not effective in introducing PDZ in thin fasteners and would even destroy them. Moreover, the main limiting factors in strengthening thin fasteners are the out-of-plane deformation during the strengthening process, ascribing to the axial movement of the tool in direct contact with the hole wall. Therefore, a new method that can overcome the abovementioned obstacles is in urgent demand for strengthening thin fasteners.

Recently, a new method, named electromagnetic cold expansion (EMCE), has been developed to strengthen the holes in fasteners [15]. The noncontact EMCE method utilizes radial Lorentz force to deform the material elastically/plastically and will not cause axial force. These inherent features make EMCE particularly suitable for extending the fatigue life of thin fasteners. However, the abovementioned work was only focused on 4-mm-thick aluminum specimens, and the influence of the circuit parameters, which are the key factors in determining the electromagnetic process, on the strengthening efficiency of the fasteners was not discussed.

In this study, a coupled finite element method (FEM) was used to investigate the influence of circuit parameters on the size of PDZ in 1.5-mm-thick 2A12-T4 specimens with a concentric hole through EMCE. To this end, the elastic/plastic behavior of the 2A12-T4 Al alloy under electromagnetic process was modeled by COMSOL Multiphysics, and the simulation results of the final radial strain were verified by the grid method. In addition, the effects of the pulse width of the pulsed current on the size of PDZs as well as the influence of the radial inward force during the unloading process on the residual stress were investigated. Finally, the fatigue life improvement of rectangle fasteners strengthened by EMCE was presented. In the following sections, the principle, design, and implementation of the developed EMCE system are firstly introduced, and then both numerical and experimental analyses are carried out in detail.

2 The basic principle of cold expansion via the electromagnetic method

The basic principle of EMCE is similar to that of the widely studied electromagnetic forming, where the pulsed Lorentz force is introduced to achieve plastic deformation inside the specimen [16–20]. During the strengthening process, an eddy current in the specimen and a pulsed magnetic field in space are generated as the pulsed current flows through the coils which are placed near a specimen. Thus, a strong pulsed Lorentz force is formed in the specimen, and its density can be expressed as

$$\mathbf{f}_L = \mathbf{J} \times \mathbf{B}$$

(1)

in which \(\mathbf{J}\) and \(\mathbf{B}\) are eddy current density and magnetic flux density in the specimen, respectively.

Generally, in the axisymmetric case, the eddy current \(\mathbf{J}\) has only one component \(J_{phi}\) along the circumferential direction, and the magnetic flux density has two components \(B_r\) and \(B_z\). Therefore, the Lorentz force density can be decomposed into

$$f_r = J_{phi} \cdot B_z$$

(2)

$$f_z = -J_{phi} \cdot B_t$$

(3)

where \(f_r\) and \(f_z\) are radial and axial components of the Lorentz force density, respectively.

Similar to the conventional hole strengthening mechanism, the EMCE requires a sufficient radial outward force to cause plastic deformation around the hole. The schematic of the EMCE system in this work is presented in Fig. 1. The system mainly consists of two sets of coils, named the inner coil and the outer coil, and each set of coils are connected in series. The outer coil is mainly used to introduce a relatively constant axial magnetic field during the EMCE process, while the inner coil is mainly used to generate a strong enough eddy current in the workpiece. All the coils and the hole of the specimen are placed coaxially.

The discharge currents of the coils are shown in Fig. 2, which consist of a long pulse width current and a short pulse width current. The former is applied to the outer coil, and the latter is applied to the inner one. The inner coil current is triggered when the current in the outer coil reaches its maximum value.

Thus, Eq. (2) can be rewritten as

$$f_r = (J_{phi \_long} + J_{phi \_short}) (B_{z \_long} + B_{z \_short})$$

(4)

in which \(J_{phi \_long}\) and \(J_{phi \_short}\) are respectively the eddy current induced by the outer coil and the inner coil, \(B_{z \_long}\) and \(B_{z \_short}\) are the axial magnetic field generated by the outer coil and the inner coil, respectively.

It should be noticed that the rising time of the inner current \(t_2 - t_1\) should be much shorter than that of the outer current \(t_1\), and the peak value of the inner coil current should be higher than that of the outer coil, hence the eddy current generated by the inner coil \(J_{phi \_short}\) is expected to be much larger than that generated by the outer coil \(J_{phi \_long}\), as shown in Fig. 3(a). Though the inner coil current is higher, the number of turns of the outer coil is several times that for the
inner coil, so the axial magnetic field can keep its direction during the whole EMCE process, as shown in Fig. 3(b).

Under this situation, Eq. (4) could be approximately expressed as

$$f_r \approx J_{\phi_{short}} \cdot B_{z_{long}}$$

indicating that the outer coil mainly aims at providing a proper background axial magnetic field while the inner coil is responsible for exciting a strong enough eddy current in the specimen. The decoupling design of the two sets of coils can generate the Lorentz force needed for EMCE.

## 3 Materials, experiment, and simulation details

### 3.1 Material

In this work, 2A12-T4 aluminum alloy specimens (Chinese standard, GB) with a diameter of 50.0 mm and a thickness of 1.5 mm were adopted to measure the radial strain of the material after EMCE. Rectangle specimens with the size of 50.0 mm * 200.0 mm were utilized to conduct the fatigue life test. The 2A12-T4 aluminum alloy is widely used in the aerospace industry owing to its high strength, excellent corrosion resistance, etc. A hole was carefully drilled and reamed to a final diameter of 6.0 mm at the specimen center.

The chemical compositions of 2A12-T4 in this paper are listed in Table 1. A uniaxial tensile test was performed to obtain the stress–strain relationship, as shown in Fig. 4. The 0.2% proof stress (initial yield stress), elasticity modulus, and Poisson’s ratio are 262 MPa, 73 GPa, and 0.33, respectively.

The Johnson–Cook constitutive model was adopted in this study to reflect the response of the 2A12-T4 specimen under a high strain rate due to the pulsed Lorentz force. Without consideration of the temperature increase in a single discharge process, which often leads to 20–30 °C of the temperature increase, the Johnson–Cook constitutive model can be simplified as

$$\sigma = (A + B\varepsilon_{eff}^n) \begin{bmatrix} 1 + C \ln \left( \varepsilon_{pe} \right) \end{bmatrix}$$

The detailed value of each parameter is presented in Table 2.

### 3.2 Design and implementation

The specific circuit model is presented in Fig. 5. The system consists of two sets of coils, driven by two independent power supplies. The trigger accuracy of the two power supplies is controlled within 0.1 µs level to generate the required currents. It should be noted that there is a crowbar branch consisting of a crowbar resistance and a diode in each discharge circuit, which can be used to alter the waveforms of the discharge current by adjusting the crowbar resistance [22].

The discharge voltages for strengthening rectangle specimen as well as details of the circuit parameters are presented in Table 3. RLC (a second-order circuit including the resistance, inductance, and capacitance) equations shown in Fig. 5 can be expressed as

$$\begin{align*}
(U_1 - U_{in}) \cdot (t > t_m) - & \left( \frac{L_1}{C_1} \frac{dI_1}{dt} + R_1I_1 \right) = 0 \\
C_1 \frac{dU_1}{dt} + & I_1 + \frac{U_1}{R_{41}} \cdot (U_1 < 0) = 0 \\
(U_2 - U_{ex}) - & \left( \frac{L_2}{C_2} \frac{dI_2}{dt} + R_2I_2 \right) = 0 \\
C_2 \frac{dU_2}{dt} + & I_2 + \frac{U_2}{R_{42}} \cdot (U_2 > 0) = 0
\end{align*}$$

![Fig. 2 Schematic of the coil currents](image-url)
in which $U_1$, $U_{in}$, $t_{tr}$, $L_1$, $I_1$, $R_1$, $C_1$, and $R_{dl}$ represent the discharge voltage for the capacitance, the terminal voltage for the inner coil, the discharge moment, the circuit inductance, the coil current, the line resistance, the capacitance, and the crowbar resistance of the inner coil system, respectively. While subscript 2 represents the parameters in the outer coil system and $U_{ex}$ denotes the terminal voltage for the outer coil.

To enhance the fatigue life of the coil sets, the Zylon fiber, with a tensile strength over 4 GPa, was used to protect the coil structure during the EMCE process. The outer coil, which was expanded due to the Lorentz force, was strengthened layer by layer. While the inner coil, which was compressed during the EMCE process, was strengthened at the outermost layer. The assembly of the coils and the specimen is given in Fig. 6. To eliminate the friction between the coil sets and the specimen as well as to avoid the surface scratch of the specimen during its deformation, the specimen was covered with polyethylene thin film and a set of insulating holders with a thickness of 1.8 mm were used during the experiment.

### 3.3 Grid method

To obtain enough data near the hole in measuring residual strain by the grid method, the grids should be small enough, and the grid boundaries should be clear enough under a microscope. In this paper, the grids were divided into an $80 \times 80$ matrix by a 4-W YAG laser, and each grid had a diameter of 300 μm and a distance of 500 μm, as shown in Fig. 7(a).

As shown in Fig. 7(b), the deformation of the grid was measured by a Nikon SMZ18 optics microscope. Fig. 7(c) presents the deformed grid transformed from a circle to an ellipse near the hole wall on the specimen. The initial grid size was determined by taking the average diameter of 10 grids, and the size of the grid along the radial direction was measured again after the EMCE process. Then, the radial strain of the specimen could be calculated by

$$
\varepsilon_r = \ln \left( \frac{d_1}{d_0} \right)
$$

in which $\varepsilon_r$ is the radial strain and $d_1$ and $d_0$ are the deformed and original grid diameters, respectively. To make the measurement accurate, the radial residual strains were measured three times along three mutually perpendicular routes.

### 3.4 Fatigue test

A total of 40 specimens including 20 “as drilled” and 20 EMCE strengthened were tested in fatigue at room temperature. The cyclic tension-tension loading test was realized by using a high-frequency electromagnetic resonance fatigue testing machine (QBG-50) with a stress ratio of 0.1, as shown in Fig. 8, and the resonance frequency was about 105 Hz. The maximum nominal net section stress levels were set to be 120 MPa, 140 MPa, 160 MPa, and 180 MPa.

### 3.5 Finite element simulation

In this study, a two-dimensional axisymmetric fully coupled numerical simulation model was developed by COMSOL Multiphysics. The electromagnetic field, the solid mechanics field, and the ordinary differential equations (ODEs) were utilized to simulate the dynamic EMCE process. The computational model is presented in Fig. 9, and it mainly consists of the coils and the specimen.

![Fig. 3](image)

*Schematic diagram of the expected a eddy current and b axial magnetic field in the specimen; the background transparent lines show the discharge current*
4 Results and discussion

To investigate the influence of the circuit parameters during the EMCE process on the size of PDZ in thin 2A12-T4 specimens, the deformation behavior of the specimens is investigated both numerically and experimentally.

4.1 Validation of the finite element simulation

The discharge currents of the two coils were separately measured by a Rogowski coil and a Pearson current transformer. Figure 10 shows both the measured and simulated coil currents, showing a good agreement between the two results. It can be seen that the current pulse width of the outer coil is longer than that of the inner coil. The long pulse width current reaches its peak value at 4.700 ms, meanwhile, the power supply for the inner coil system is triggered, and the corresponding current reaches its maximum value at 98 μs. It can be seen that an oscillation attenuation waveform of the inner coil occurs during the current falling edge in the experiment due to the minor inductance in the crowbar circuit, which is neglectable as discussed in Appendix 1.

Figure 11 shows the comparison of radial residual strain obtained by the grid method and the FEM simulation, where the simulation results basically match with the experiments. It can be seen that the compressive radial strain reaches its maximum value around the hole wall and then decreases sharply away from the hole wall within 4 mm, and after that, the strain remains approximately zero. The strain gradient is very high around the hole wall, though the physical size of the etched grids limits the measuring accuracy of the strain at these high-gradient areas, the total trend, as well as the magnitude of the measured residual strain between the two results, are comparable.

It must be stated that during the EMCE process, very few parameters, including discharge current and the final residual strain, can be experimentally obtained, and these obtained results are in good agreement with the FEM simulations. In addition, considering the main purpose of this paper is to discuss the effect of circuit parameters on the size of PDZ, the following analyses are mainly further performed based on FEM simulations.

4.2 Distribution of residual stress

Figure 12(a) presents the Lorentz force inside the Al plate during the EMCE process with the circuit parameters given in Table 3. A considerable Lorentz force can be generated only when the power supply for the inner coil is triggered. When $t < 4.672$ ms and $t > 4.958$ ms, the value of radial Lorentz force component is less than one-tenth of that at $t = 4.745$ ms. The radial Lorentz force required to deform the specimen is induced by a hoop eddy current and an axial magnetic flux density. Figure 12(b) gives the spatial
distribution of the eddy current density, the magnetic field, and the Lorentz force density. As previously expected, the magnetic field is mainly oriented along the axial direction (downward), and the eddy current is along the hoop direction (clockwise), and finally, the Lorentz force is radially outward. Though there exists an axially downward Lorentz force component near the specimen surface as shown in Fig. 12(b), it can be eliminated to zero due to the symmetry geometry.

The dynamic hoop eddy current, axial magnetic flux density, and radial Lorentz force density at point A (see Fig. 12(a)) are shown in Fig. 13. It can be seen that the hoop eddy current reaches its negative peak value at 4.745 ms (set clockwise as positive), meanwhile, the upward axial magnetic flux...
During the EMCE loading process, both the radial and hoop stress components are tensile, as shown in Fig. 14(a), and this is quite different from the conventional hole-wall-push cold working method, where the radial stress component is compressive. Radial compressive stress is another important factor that causes local warpage in addition to axial force. However, in the EMCE process, this can be avoided due to the tensile stress state in both hoop and radial directions.

The EMCE process introduces a nonuniform stress field along the radial direction, resulting in a nonuniform elastic and plastic deformation field. The final radial strain near the hole wall is higher than that at the outer area of the specimen, as shown in Fig. 14(b). As the radial outward Lorentz force is removed, material near the hole wall is constrained by the outer material, and thus the residual compressive stress is produced, as shown in Fig. 15(a). Such a high strain rate is sufficient to harden the material, making it show a completely different constitutive relationship compared with that under quasi-static state. Figure 15(c) shows that there is no axial variation for the hoop residual stress, indicating that the deformation is uniform either on the surface or inside the specimen.
4.3 Effect of the pulse width of the inner coil current

As discussed above, the main reason for producing the residual stress is the interaction of the axial magnetic flux density and the hoop eddy current. Owing to a longer pulse width of the outer coil, the axial magnetic flux density remains nearly constant during the whole discharge process of the inner coil, so it has little effect on the final residual stress. The eddy current, however, is largely influenced by the pulse width of the inner coil. Therefore, it should be an effective way to adjust the size of PDZ by varying the pulse width of the inner coil. In the following, a series of simulations based on different pulse widths of the inner coil were conducted, while the total energy for the inner coil discharge system was set to be constant (1000 J).

Figure 16 shows the maximum von Mises stress distribution during each discharge process and the correlation between short pulse width and the size of PDZ. Here, a cutting...
line of $z = 0$ mm is chosen for analysis, which represents the middle plane of the specimen and where the axial Lorentz force is ignorable. It can be seen that the larger capacitance, the wider the pulse width. However, the size of PDZ shows a non-monotonic relationship with the capacitance. The optimum capacitance is around 40 $\mu$F, where the size of PDZ occupies almost all the area of the specimen. With a larger or smaller capacitance, the size of PDZ decreases. In addition, it can be found that when the width of the short pulse current ($W_s$) is 64 $\mu$s, the size of PDZ is very large; however, there is little PDZ when $W_s = 170$ $\mu$s. This indicates that the Lorentz force is too weak when the width of the coil current is too long, and this is mainly owing to the induced weak eddy current inside the workpiece. It should be noted that the stress state in Fig. 16(a) is not the quasi-static value, and the value higher than the initial yield stress (262 MPa) is mainly attributed to the strengthening effect resulting from both the plastic deformation and the high strain rate.

The reason why the size of PDZ decreases with a sharper pulse width as the capacitance is smaller than 40 $\mu$F could be given in Fig. 17(a). When $C_1 > 40$ $\mu$F, the peak value of discharge current increases slowly as the capacitance decreases, and the larger PDZ area is mainly dominated by shorter pulse width. When $C_1 < 40$ $\mu$F, although pulse width is further shortened, the discharge current magnitude decays dramatically, which is unfavorable for the EMCE process. This phenomenon can be attributed to the response of inductive reactance under high-frequency pulsed current, as shown in Appendix 2. The corresponding hoop residual stress after the EMCE process is plotted in Fig. 17(b). As the capacitance decreases, the compressive hoop residual stress near the hole wall firstly increases and then decreases and reaches its maximum value when $C_1 = 40$ $\mu$F. This trend is consistent with the results for the size of PDZ.

### 4.4 Effect of the crowbar resistance

The crowbar resistance of the inner coil takes into effect during the unloading process. It does not influence the size of PDZ but has a great impact on the final residual stress. As the inner coil current decreases after its peak value, a reversed eddy current will be excited inside the specimen, thus producing a radial inward Lorentz force. A larger crowbar resistance can lead to a sharper decrease of the coil current, as shown in Fig. 18.

To investigate the effect of crowbar resistance, the discharge currents of the inner coil for $R_{d1} = 1$ m$\Omega$ and 200 m$\Omega$ were chosen for comparison. Five feature points on each current curve are picked; as shown in Fig. 19(b), they are corresponding to, before the inner coil is discharged (A and A'), the radial outward (positive) Lorentz force is maximum (B and B'), the radially Lorentz force is minimum (C and C'), the radial inward (negative) Lorentz force is maximum (D and D') and the radially Lorentz force is minimum again (E and E'). The corresponding eddy current, axial magnetic flux density, and radial Lorentz force density at each point are plotted.

### 4.5 Change in plastic strain

As the pulse width increases, the plastic strain decreases. This phenomenon can be attributed to the decrease in the size of PDZ, which results in a larger plastic strain. It is found that the plastic strain is smaller than 0.001 when $W_s > 100$ $\mu$s, which indicates that the plastic deformation is totally ignorable. As the pulse duration increases, the plastic strain decreases as shown in Appendix 2.
in Fig. 20, which also roughly reflects the whole EMCE process. The influence of the axial magnetic flux density can be eliminated since it is mainly negative during the whole process and does not contribute to the reversed radial Lorentz force (although the axial magnetic flux density is partially reversed near the hole wall, see Fig. 20(C), (C'), and (D), the eddy current at those areas is too weak, and the corresponding Lorentz force is ignorable.). As stated above, the eddy current reverses at both D and D', and it is much stronger when \( R_{d1} = 200 \text{ m}\Omega \); therefore, the radial inward Lorentz force density is stronger.

The final hoop residual stress is given in Fig. 21. It can be seen that crowbar resistance is a factor that cannot be disregarded in determining the EMCE strengthening performance. The residual stress varies even though the sizes of PDZ under the maximum load are the same. A larger crowbar resistance causes a stronger reversed radial Lorentz force inside the specimen, producing smaller residual stress. Moreover, it can be seen that the residual stress is weakened near the hole wall, and it is more obvious under a larger crowbar resistance. This might be attributed to that the reversed Lorentz force, which locates at the middle region of the specimen, is stronger under a larger crowbar resistance. The decrease of the compressive residual stress near the hole wall is not a preference for hole strengthening since the fatigue cracks...
are mainly initiated at the hole wall. This is also the reason why the crowbar circuit of the inner-coil discharge system was set to be as small as possible during experiments, as stated in Section 4.1.

### 4.5 Fatigue test after EMCE

To verify the effectiveness of the proposed method in strengthening thin fasteners, a series of fatigue tests were performed, and the discharge parameters for the specimens are shown in Table 3. The Basquin’s power function was used to fit the fatigue data, and the function can be expressed as [23]

\[ S_a = aN_f^b \]  

in which \( S_a \) is the stress amplitude, \( N_f \) means the fatigue life, and \( a \) and \( b \) are the fitting parameters of the fatigue data.

It can be seen from Fig. 22 that the EMCE method has a positive effect on 1.5-mm-thick 2A12-T4 Al fasteners. A significant enhancement of the fatigue life is achieved after the EMCE process. The gain in fatigue life depends on the maximum applied stress, and they are 5.49, 3.50, 2.51, and 1.67 times when the maximum applied stress is 120 MPa, 140 MPa, 160 MPa, and 180 MPa, respectively. It is obvious that the fatigue life improvement under the EMCE method is appreciable, and the improvement of the fatigue life can be attributed to many aspects. Firstly, a considerable compressive hoop residual stress is produced around the hole utilizing the EMCE process inside the specimen, counteracting part of the external applied tensile stress during the fatigue test. Secondly, the EMCE process produces no damage to the hole wall, and to a certain extent, the potential source of fatigue cracks is reduced. Thirdly, the hoop residual stress distributes uniformly along the thickness direction, preventing the preferred generation of the fatigue cracks where the hoop residual stress is lower along the thickness direction.

### 5 Conclusions

In this study, a dual-coil electromagnetic cold expansion method was developed to introduce a large PDZ area in 1.5-mm-thick 2A14-T4 specimens. The influence of the circuit parameters on the size of PDZ as well as the residual stress was analyzed. The main conclusions are as follows:

1. The electromagnetic strengthening method can generate sufficient force to deform specimen with tensile stress along both hoop and radial directions during implementation, produce a high compressive hoop residual stress distributed uniformly along the thickness direction, and improve the fatigue life of 1.5-mm-thick specimens by several times.

2. It is found that there exists an optimal capacitance (about 40 \( \mu \)F in this work) to achieve the maximum size of PDZ under the same discharge energy for the inner coil, which can be attributed to the competition between the current pulse width and current magnitude.

3. It has been demonstrated that the crowbar resistor in the discharge circuit of the inner coil has an impact on the unloading process. The smaller the resistance of the crowbar resistor, the slower the decay of the inner coil current in the falling stage, which can reduce the reversed Lorentz force in the unloading process.

Overall, the obtained results clearly show that the EMCE method is very effective in strengthening the thin fasteners. It can make up for the deficiency of serious axial deformation and a small plastic area caused by the traditional methods when strengthening thin fasteners.
Appendix 1

The author has fitted the detected oscillation attenuation waveform for the inner coil current and substituted it to FEM and compared it with the situation when this oscillation attenuation waveform was not considered (by solving circuit equations). The results showed that the negative (radially inward) Lorentz force was comparable with the case calculated by circuit solution, and it did not influence the final results significantly.

Appendix 2

For simplicity, a single inner coil under pulsed currents was utilized, and the response of inductive reactance and the circuit’s resistance was illustrated in Fig. 24. The inductance of the coil can be given via:

\[ Q_m = \frac{I^2 L}{2} \]  

(A1)

in which \( Q_m \) is the magnetic energy, \( I \) represents the coil current, and \( L \) indicates the inductance of the coil. And the inductive reactance can be obtained by

\[ X_L = \frac{2\pi}{T} L \]  

(A2)

\( X_L \) is the inductive reactance, \( T \) means the period of the discharge current, and usually four times of the rising time of the pulsed current is used.

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**Fig. 23** Simulation results to study the influence of oscillation attenuation waveform: a the fitted oscillation attenuation waveform current, b the total Lorentz force, c the final radial residual strain, and d the hoop residual stress

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**Fig. 24** Simulation results of the inductance of a single-coil at high frequency for constant energy (2 kJ): a coil current, b inductive reactance
Availability of data and materials All data generated or analyzed during this study are included in the present article.

Author contribution Xiaolei Xu: experiment conceiving and designing, finite element simulation, original draft writing, and funding acquisition. Huihui Geng: electromagnetic experiment conducting, and experimental data analyzing. Qingshan Cao: fatigue test performing and strain measurement conducting. Quanliang Cao: supervision, conceptualization, methodology, funding acquisition, reviewing, and editing. Liang Li: supervision, conceptualization, methodology, reviewing, and editing. Xiaoping Ouyang: supervision, methodology, reviewing, and editing. All authors have read and agreed to the published version of the manuscript.

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Declarations

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