Current Research Developments of Electromagnetic Joining Technology in China-A Review

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Abstract: With the increasing applications of multi-material structures in lightweight vehicle, traditional joining techniques are highly challenged in joining dissimilar materials. To meet the multi-material structures requirements of lightweight design, electromagnetic joining (EMJ) technology, including electromagnetic riveting (EMR) and magnetic pulse welding (MPW), developed rapidly in recent years, which can achieve good connection performance for complex-shaped structures and dissimilar materials. This paper presents a comprehensive review of the research progress of the EMJ technology in China. Moreover, this review aims at providing a guideline for researchers engaged in electromagnetic joining technology and other connecting processes to further improve the level of lightweight vehicle design and manufacture. Firstly, the development history and status of EMJ were presented. Then the basic joining principles and characteristics of EMR and MPW were analyzed in detail. Subsequently, the investigation of joints formation mechanism, mechanical properties of joints and equipment development of EMR and MPW techniques were reviewed and analyzed. Specially, the operating principle is described along with various factors affecting the mechanical and microcosmic properties of joints. Finally, the future development trend of the EMJ technology based on the current research progress is highlighted.

Keywords: Electromagnetic riveting, magnetic pulse welding, joining mechanism, mechanical properties, dissimilar materials, joining equipment.

1 INTRODUCTION

Due to the increasing demand in lightweight vehicle design in recent years, the high specific strength materials such as aluminum alloy, high strength steel and composite materials has been widely applied in vehicle body [1-3]. However, the different melting point, thermal conduction and thermal expansivity between dissimilar materials make the conventional fusion welding invalid [4, 5]. Current common connection methods, including bolting [6-8], bonding [9] and riveting [10-12] have corresponding limitations in joining dissimilar materials structure. Detailly, the aging trend of the adhesive bonding resulted in the unreliable connection, while the looseness of bolting could reduce the joining quality. Furthermore, the conventional riveting technology would cause the driven head cracks in riveting big diameter and high strength rivet [13, 14]. Those damages limited the improvement of the connection level of the multi-structure lightweight vehicle. Hence, advanced joining methods are important to enhance the current level of design and manufacture of lightweight vehicle.

The electromagnetic joining technology (EMJ), including electromagnetic riveting (EMR) and magnetic pulse welding (MPW) technology are developed recently to take the advantages of fast connection efficiency, high impact force, deformation stability, non-polluting and easy control [15, 16]. Since the EMJ process produced no thermal distortion and heat-affected zone in the connection structure, the mechanical strength and corrosion resistance of similar and dissimilar material EMJ joints had been significantly improved [17-19]. Moreover, the performance targets of EMJ joints were accorded well with the service performance requirement of the assembly [20]. Thus, the propagation of the EMJ technology could efficiently promote the application in vehicle manufacturing industry. Recently, the number of research papers associated with electromagnetic riveting and magnetic pulse welding has rapidly intensified, as shown in Fig. (1).

In China, the research progress of EMR technology began in the 1980s. High-voltage fixed and handled EMR equipment was first developed to solve the technical challenges for titanium alloy rivets [21]. Due to the expensive equipment price and the poor equipment reliability, the new
generation EMR equipment of low voltage and miniaturization was required [22]. Thus, the low-voltage EMR equipment with a maximum voltage within 500V was manufactured in the 1990s [23]. Moreover, the vibration reduction and noise absorbing of electromagnetic riveter were also investigated [24]. After the development of both control and capacitance technology, the low-voltage EMR equipment was quickly and widely applied since 2000s. Up to now, the electromagnetic riveting equipment was gradually transformed from low-voltage, handheld equipment to automated equipment [25].

In the 1980s, the Chinese universities and research institutions first conducted research in MPW to meet the technical challenges in welding dissimilar materials [26]. With recent developments in the MPW technique, MPW has been used to realize the potentiality of dual welding materials. Scholars from china have performed detailed research on the MPW of aluminum-steel structure [27], aluminum-CFRP (carbon fiber reinforced polymer) structure [28], steel-copper structure [29] and aluminum-magnesium structure [30]. At present, the most domestic research of MPW focused on process development, simulation analysis, bonding interface appearance, metallurgical bonding mechanism, mechanical performance, etc.

As a reliable multi-material connection technology, electromagnetic joining technology has become a topic in connection technology research field. This article reviewed the developed progress of electromagnetic joining technology in China. In this review, the basic principle of electromagnetic riveting and magnetic pulse welding methods were reviewed in section 2. In sections 3 and 4, the electromagnetic riveting and magnetic pulse welding technology were reviewed and analyzed from three aspects: formation mechanism of the joints, mechanical properties, and equipment development.

Furthermore, the future development of electromagnetic connection technology was prospected in section 5.

2. BASIC PRINCIPLE AND CHARACTERISTICS OF EMJ

Electromagnetic riveting and magnetic pulse welding technology, as the two main aspects of the electromagnetic joining technique, have a significant difference in the basic principle and the characteristics. The electromagnetic riveting process mainly consisted of two parts: pulse generator and joining equipment. The electromagnetic equipment was simplified as a typical Resistor-Inductor-Capacitor (RLC) oscillating circuit, which generated magnetic field force to provide riveting energy in the following details. Diagram of the EMR system principle was shown in Fig. (2). Firstly, the predetermined discharge energy in the capacitors discharged through the coil when the switch was closed. Then, an instantaneous electromagnetic field was generated around the circuit according to Faraday’s law of electromagnetic induction. This instantaneous electromagnetic filed produced the reverse eddy current in the driver plate and formed a repulsive magnetic force between coil and driver plate. After the generation, the impact load finally acted on the rivet in the form of a stress wave and drove the rivet to join the sheets. Upon the difference in the riveting equipment, the EMR could be divided into electromagnetic self-piercing riveting [31], electromagnetic rivet hybrid joining [32], electromagnetic nailing [33], etc.

Unlike EMR process, magnetic pulse welding technology directly used magnetic field force to drive the conductive workpieces. The welded workpiece in MPW process was defined as flyer plate/tube and base plate/tube upon the electric conductivity. Due to the instantaneous electromagnetic field, the flyer plate/tube (with better electric conductivity)
suffered huge repulsive force and was accelerated to collide onto the base plate/tube. The high-speed impact produced metallurgical bonding between two plates/tubes. In the MPW process, the jet emission provided a clear surface for the metallurgical bonding, while the suitable impact velocity and impact angle were essential for the successful welding. Fig. (3) shows the MPW principle for both sheet and tube connections.

![Diagram of the EMR system principle](image)

**Fig. (2).** Diagram of the EMR system principle [34]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

### 3. RESEARCH PROGRESS OF EMR

#### 3.1. Formation Mechanism of Rivet

The Electromagnetic Riveting (EMR) was a dynamic impact loading process within milliseconds, causing the formation mechanism of rivet more complex with the influence of stress-wave and high-speed impact [36]. Comparing to the traditional riveting method, EMR could achieve a more uniform interference-fit [37]. Thus, many researchers have investigated the effect of interference-fit on EMR process. Through the experimental research, the ideal interference fit of EMR needs proper voltage and appropriate extension [38]. The interference-fit values could effectively increase with the increasing discharge energy [39]. In addition, Zhang et al. established the relationship between interference-fit values and process parameters (riveting forces and rivet shaft length) based on the theoretical model on an interference fit for EMR process [40].

During the EMR process, the temperature rises in the rivet causing from plastic deformations could not be timely transferred to the ambient within milliseconds. Consequently, the Adiabatic Shear Bands (ASBs) were usually formed in the approximate adiabatic environment [41]. Many Chinese researchers investigated the formations mechanism and microstructural evolution of ASBs in titanium and aluminum rivets. Gong et al. studied the microstructure evolution of the rivet head and the initiation and expansion process of ASBs by the discretized rivet specimens [42]. The results showed that the shear bands were firstly initiated in the central area and the diagonal area, while the initiation of primary and secondary shear bands was not synchronized. Deng et al. [43] found that the evolution mechanism of Titanium Grade 1 rivet was mainly the twinning deformation when the adiabatic temperature does not affect the material flow. Subsequently, the sub-grain rotation completed the dynamic recrystallization with the increase of rivet deformation, as shown in Fig. (4). Through the sequential electromagnetic-thermal-mechanical coupling model carried out by means of ANSYS and LS-DYNA software, the formation of ASBs and the effective strain distribution were systematically simulated, and the maximum temperature in the ASBs was found of 252 °C [44]. Besides, the highest temperature in the ASBs was found to be decreased by the decrease in the die angle through the axisymmetric model established based on ABAQUS [45]. The dimple structures and concave die in the headless EMR process were found to effectively reduce the shear effect on 45° direction of rivet head based on the simulation results by ANSYS, causing that the shear band could not be obviously observed [46].

#### 3.2. Mechanical Properties of the Joints

Comparing to the convention riveting technique, EMR technique has obvious advantages in titanium rivet and composite structure riveting. The mechanical properties of CFRP/Al EMR joints under static loading and high-speed loading both exhibited obvious strengthening than convention riveting joints. Moreover, the study of process parameters and rivet die provides more methods to increase the mechanical performance of EMR joints.

Due to the excellent characteristics of low density, superior corrosion resistance, and high strength-to-weight ratio, titanium rivets have also been widely used in aircraft structures [47, 48]. However, the hard-forming of titanium alloy at room temperature results in the technical challenges of a traditional riveting method such as the cracks in the rivet head [49, 50]. To solve the existing problem, EMR method was adopted to join the titanium rivet with the appropriate key parameters like rivet die dimension, extending length and riveting voltage [51]. Through the precast aperture matching tests, the EMR was far superior to pneumatic riveting in forming titanium alloy rivet and improved the riveting quality, as shown in Table 1 [52]. EMR could effectively achieve the interference riveting of titanium alloy rivets through the forming of the adiabatic shear zone [53]. By the comprehensive consideration of material strain hardening, strain rate hardening, thermal softening effects, friction, and structural nonlinearity, the 3D finite model was established on the ABAQUS software to understand the influence of the temperature field on the forming of rivet head and adiabatic shear zone. The results showed that the strain in the shear zone was highly concentrated, while the distribution of high temperature area basically coincided with the shear zone. The highest temperature was up to 500°C, which exceeded the recrystallization temperature [54].
Fig. (3). MPW principle for sheet and tube connections: (a) sheet connection; (b) tube connection [35, 28]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (4). Microstructure distribution in the different location of Ti Grade 1 rivet head (a) schematic of microstructure observation; (b) location a; (c) location b; (d) location c; (e) location d; [43]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Table 1. Maximum tensile load of samples under pneumatic riveting and EMR [52].

<table>
<thead>
<tr>
<th>Mechanical Performance</th>
<th>Φ4 mm Rivet</th>
<th>Φ5 mm Rivet</th>
<th>Φ6 mm Rivet</th>
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<tr>
<td>EMR</td>
<td>6500N</td>
<td>10900N</td>
<td>11000N</td>
</tr>
<tr>
<td>Pneumatic riveting</td>
<td>6400N</td>
<td>9970N</td>
<td>9010N</td>
</tr>
<tr>
<td>Enhancement</td>
<td>1.56%</td>
<td>9.32%</td>
<td>22.08%</td>
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Composites materials like CFRP have been widely applied in vehicle and aircraft structures [55, 56]. Comparing to the metal materials, the brittleness, anisotropy, low transverse strength of composite materials makes the conventional riveting method complex and critical [57-59]. Due to the advantages of EMR technology in joining composite materials, many efforts have been conducted to investigate the microstructure, mechanical properties, and failure mechanism of the composite electromagnetic riveted structures [60, 61].

Throughout the mechanical and microstructure behaviors of CFRP/Al electromagnetic riveted lap joints, the rivet squeezing effect was found to cause the bending of the Al sheet and the damage of the CFRP sheet under static load, as shown in Fig. (5) [34]. Cao and Cardew-Hall designed a special washer and studied the clearance between shaft and aperture wall. The results showed the washer and the appropriate clearance could effectively restrict the expansion of shaft and prevent the damage of the composite [62]. The microtopography analysis after the tensile-shear test presented the CFRP damage extent degree and rivet leg expansion had an important role on the strength of electromagnetic self-piercing rivet (E-SPR) joints [31].

As for the dynamic and fatigue mechanical performance, Cui et al. investigated the failure behaviors of CFRP/Al EMR joints under high-speed loading and analyzed the full field strain of both sheets. The results revealed the corresponding relationship of the failure mode (Fig. 6) [63]. Jiang et al. compared the shear failure behaviors between CFRP/Al and High strength steel/Al E-SPR joints under different loading speeds [64]. The tensile test results of the CFRP/Al riveted joints showed the joints had less maximum shear load at the lower loading speed than it at the higher loading speed [65]. Besides, the hole expansion of CFRP/Al EMR joints caused three typical fatigue failure modes associating with driven head dimensions and stress level in the sheet [66].

To further reduce the rivet damage, the effects of process parameter and rivet die on the mechanical performance were further studied. Discharge energies could influence the mechanical and fatigue properties by the direct function on the deformation of rivet head [66]. Specifically, the larger deformation in the driven head caused the tighter interference-fit values, which further enhanced the shear fatigue properties. By the experimental evaluation of mechanical properties, the tail dimension of rivet was found to be essential to the pull-out strength and failure mode of riveted joints [67]. The rapture modes for pull-out samples with different rivet tail heights were shown in Fig. (7). To design the most appropriate rivet geometry, orthogonal experiment method, cross-section observation, mechanical property, and grey correlation theory were adopted to obtain the joints with optimal mechanical properties [68].

During the rivet forming process, the structure parameters of rivet die could effectively influence the excessive material flow, shear stress levels, and the microhardness. Cui et al. [69] found the slope angle of rivet dies could influence
Fig. (6). The failure process and failure positions of the EMR specimens under high-speed loading [63]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (7). Rapture modes for pull-out samples with different rivet tail heights: (a) rivet tail with 5- or 6-mm height; (b) rivet tail with 7 mm height; (c) rivet tail with 8 mm height [67]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).
Fig. (8). Comparison of load-displacement results between baseline and optimal design: (a) shear load-displacement results; (b) pull-out load-displacement results [71]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (9). Low-voltage handheld EMR equipment: (a) schematic of the equipment; (b) the assembly picture of the equipment [23]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

the microstructure layout in the rivet head. Besides, special rivet dies obviously enhanced the pull-out performance of the EMR joints and inhibited the formation of ASBs. The rivet joints with special rivet die had a lower stress level than the flat die because of the effect of cyclic impact and fretting wear damage [70]. Based on the effect of the rivet die, Qin et al. [71] conducted the parameter optimization procedure of rivet dies to improve the pull-out and shear strength of EMR joints by integrating ANSYS, MATLAB, LS-DYNA and a calculator on Isight platform (Fig. 8).

3.3. Equipment Development in EMR

In the past few years, low-voltage handheld EMR equipment has been developed to meet the demand of the aerospace industry. Throughout designing a hand-held electromagnetic riveter, J.J. Cui [23] studied the coordination of the internal component parameters inside the riveter, which lay the foundation for the mastery of low-voltage riveting technology. The schematic and the assembly picture of the riveter is shown in Fig. (9). L.Q. Sun [72] proposed a riveter based on the theoretical analysis and numerical simulation results. The riveting experiments confirmed that the forming ability of the riveter met the technical requirements and the riveting recoil force was far below the Chinese military standard. Jiang et al. [73] conducted the EMR experiments using round head riveting equipment and slug riveting equipment (Fig. 10) to study the effect of locking mode on the mechanical performance and failure behavior.

Furthermore, the working principle of the EMR, the development of discharge circuit and the distribution of the
electromagnetic field characteristic were systematically explored to better design the equipment [74, 75]. The coil was an essential component to convert the electricity to kinetic energy. Thus, many types of research have been conducted on the effects of coil structural parameters on the riveting force, rivet deformation degree and energy conversion by both experimental method and numerical method [76]. The results showed that the performance of riveting force and energy conversion between different type of coils was distinguished. The trapezoid cross-section had the best performance of riveting force among rectangular, pentagonal, and circular types [77].

In order to enhance the application breadth of EMR system, many additional devices are designed to broaden the functionality of the system. Yang et al. designed an electromagnetic heating riveting control system based on digital signal processing (DSP), in which the rivets were heated by medium frequency electromagnetic induction heating principle [78]. Aiming at the alignment problem of manual electromagnetic riveting, a three-coordinate electromagnetic riveting bracket system based on industrial smart cameras was designed [79]. The semi-automatic EMR system, including accurate angle automatic adjustment and vibration reduction system, was designed to realize automatic riveting function [80].

4. RESEARCH PROGRESS OF MPW

4.1. Welding Interface Mechanism

Due to the high-impact velocity in the MPW process, the morphology and bonding mechanism of welded joint interface were different from the traditional welding technology. Inferring the relationship between the bonding mechanism and the performance of the joint through the analysis of the morphological characteristics of the welded joint interface became a consensus.

The welding interface between Al/Al-Li MPW joints was divided into 4 zones: the molten zone, the shear molten zone, the sine wave interface zone, and the flat interface zones [81]. From the SPH simulation and theoretical analysis of Al-Fe joint, the local melt is generated in the weld interface. The local melt and the fast solidification led to the amorphous structure and the transition zone in the welded interface, as shown in Fig. (11) [82]. Cao et al. [83] analyzed the connection mechanism by combining fluid mechanics and wave dynamics. The minimum collision speed for forming Al-Al welded joints and the waveform interface were 90.12 m/s and 71 m/s, respectively.

Welding process parameters had strong impact on the morphology and characteristics of the bonding interface. The wave size and the thickness of transition zone increased significantly with the increasing thickness of and the gap between the welded sheets [84]. In the Al-Copper MPW joints, the grain size of the copper base metal could affect the interface morphology of the joints. The interface waveform between the copper plate and the aluminum base material which was annealed at 450 °C was the most obvious and the thickness of the transition zone was the largest [85]. The average thickness of transition layer in the welded area of AA3003-TC4 joints had a significant increase from 1.6 to 5.5 μm with the discharge energy changing from 25 to 35 kJ, as shown in Fig. (12) [86]. The temperature in the heat preservation had great influence on the grain structure morphology on the magnesium sheet in the Al/Mg joints. The intermetallic compound layers would generate at the interface when the temperature was above 150 °C [87].

4.2. Mechanical Properties

With advantages over traditional welding technology, the MPW provides a novel strengthening method for welding dissimilar materials [88]. Typically, the thin-walled CFRP and aluminum tubes could be connected by the MPW structures shown in Fig. (13) [28]. Over the past few years, the intensive research of MPW technology mainly focused on the process parameters, mechanical performance characteristic and new welding structures to increase the mechanical properties of MPW joints.

Due to the broad application, the effect of welding parameters such as discharge voltage, workpiece gap and overlap length on the dissimilar material MPW was systematic.
Fig. (11). (a) SEM images of the Al-Fe interface, (b) SPH simulation of the wave morphology in the Al-Fe interface, (c) Temperature distribution around the shear wave; [82]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (12). The average thickness of transition layers in AA3003-TC4 joints under different discharge energies of (a) 25 kJ, (b) 30 kJ and (c) 35 kJ [86]. (A higher resolution / colour version of this figure is available in the electronic copy of the article).
investigated by the researchers [30, 89]. Detailly, the workpiece gap and overlap length had a great influence on the collision angle, while the discharge voltage had a relative greater effect on the collision velocity [90]. Due to the great influence of the workpiece gap, Kong and Li [91] found the tensile strength, elongation after fracture, impact absorption of welded joints appeared to increase first and then decrease with the workpiece gap increasing from 0.1 mm to 0.2 mm. Through the simulation results by ANSYS/Multiphysics, the collision velocity of the welding points obviously increased with the rise of the discharge voltage, and the micro-interface of inner and outer tubes produced regular sawtooth waves when the collision velocity reached 350m/s [27]. Besides, the variation of discharge voltage could affect the microstructure performance. The mechanism of the joints could change from mechanical connection into metallurgical connection as the discharge voltage increasing [92]. The critical thickness of the inner tube increased with the increasing discharge voltage [93].

Magnetic pulse welding was the non-contact solid-state welding technology, which could avoid the fragile intermetallic phases and heat-affected zone in the metal lap joints [94, 95]. Fig. (14) showed the microstructure of the transition zone and the line scanning spectrum results across the transition zone of HC420LA-AA5052 joints. The scanning line indicated the mixed composition of Al and Fe (probable binary phase FeAl3 according to the element ratio) in the transition zone. Due to the welding interface, the mechanical strength of the well welded MPW lap joints could be higher than the weaker base metal [96]. Under the proper discharge energy, the intermetallic compound FeAl2 and ultra-fine grains were generated in the intermediate layer in Fe-Al joints [97].

In China, many scholars conducted the welded joint performance tests to analyze the formation mechanism and influence aspects to further promote the industrial application of the MPW process [98, 99]. Geng et al. [35] studied the
mechanical performance and fracture behavior of the Al-Fe MPW joints through quasi-static and dynamic tensile experiments. The results in Fig. (15) showed that the maximum shear load of MPW joints under 15m/s tensile speed was 22% larger than it under 2mm/min, which revealed the MPW joints had the positive strain rate sensitivity. The Salt spray corrosion test results showed the mechanical performance of Al-Fe MPW lap joints had obvious degradation in the salt spray corrosion environment, and the corrosion first generated at the end on both sides [100]. In order to investigated the formation mechanism of the MPW joints, Li et al. [101] proposed the 3D multi-physic numerical simulation on COMSOL Multiphysics software to study the distribution of the plastic deformation, Lorentz force, induced eddy current, and magnetic flux. All the factors showed the multilayer elliptical continuous equivalent distribution, which were consistent with the macro morphology of the MPW lap joints.

Except the common overlap magnetic pulse welding, researchers developed some new methods to broaden the application range of MPW. Peng et al. [102] conducted the comparative research among magnetic pulse welding, adhesive bonding, and magnetic pulse weld bonding (MPWB) process. Compared to the MPW joint, the lap-shear tensile test showed the peak load of MPWB joint increased from 3.19 to 6.09 kN and the energy absorption increased from 5.83 to 41.06 J. Deng et al. [103] designed a field shaper to achieve the magnetic pulse spot welding of metal material. By using the high strength coil system with the field shaper, the aluminum sheet could be effectively actuated to weld the stainless-steel sheet. The exterior of the welded area in the workpiece is shown in Fig. (16).

4.3. Equipment Development in MPW

In order to speed up the process improvement and innovation in MPW, many welding workers put forward new
ideas and carried out exploratory experiments to ameliorate the MPW system. In the discharge system, welding coils had the function of conducting current and establishing the magnetic field. Thus, the distributions of magnetic field and impact force could be manipulated effectively through coil design and optimization [104]. Deng et al. [105] proposed a new dual-stage coil system in MPW process to enhance the welding performance of aluminum sheets, as shown in Fig. (17). Comparing to the common MPW system, the extra coil generated a background magnetic field with a relative long pulse to increase the electromagnetic force.

The magnetic field shaper worked between the sheets and the coil was a practical welding tool, which could concentrate the magnetic field and strengthen the electromagnetic force on the welding area. Zhang et al. [106] designed a novel field shaper with a slow-varying central hole to enhance the peak value and the uniformity of the electromagnetic force distribution. Yu et al. [107] proposed a uniform pressure electromagnetic actuator (UPEA) to join AA 1060 aluminum alloy to Q235 steel alloy sheets. The tensile results showed the joint strength with UPEA was higher than the weaker parent sheet.

CONCLUSION AND FUTURE OUTLOOK

Due to the significant advantages in joining multi-material structure, EMJ technology has been widely researched in China to meet the challenges in automotive lightweight process. This paper presents a comprehensive review of the fundamental research and engineering application of the EMJ. The principle, the development history and typical applications of electromagnetic riveting and magnetic pulse welding were introduced in detail. Moreover, the research status of joints interface mechanism, mechanical performance and the joining equipment of EMR and MPW were systematically reviewed and analyzed. Especially, the factors affecting the mechanical and microcosmic properties of joints were comprehensively presented. Throughout the review work, some technical issues should be addressed before further application of EMJ technology. For example, the service life of working coil should be further enhanced by reducing the recoil force. Besides, the parameter optimization process should be conducted in improving the EMJ process. In summary, the outlook of future development of EMJ process are as follows:

(1) Improving the reliability of EMJ system: the automated EMJ system with high reliability and the high strength working coil with good service performance should be developed to meet the high production rate in automobile manufacturing.

(2) Broadening the connection structure of EMJ joints: the current research mainly focused on overlap joints structure with dissimilar materials. The research should be more stressed on special structures such as loop shape and long straight pipes, which are widely applied in automotive industry. Conducting the EMJ process research of various joint form is very necessary.

(3) Developing the high-power and low-voltage EMJ equipment: at present, the lack of high-power and low-voltage electromagnetic connection equipment would limit the application of EMJ. Thus, the development of the EMJ equipment should speed up.

(4) Combining the advantages of EMJ method with other connecting methods: more attention should be paid to the
development of new composite joining methods that taking the advantage of both EMJ and other connection technologies. (5) Conducting the systematic parameter process of EMJ technology: the existing parameter research of EMJ process was concentrated on single parameter optimization, while the process parameters on the EMJ process have a strong coupling effect. Therefore, the EMJ process parameters need to be systematically investigated and optimized.

NOMENCLATURE PART WITH UNITS

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<th>Symbol</th>
<th>Unit</th>
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<td>Electromagnetic Joining</td>
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<td>EMR</td>
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<td>Electromagnetic Riveting</td>
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<td>MPW</td>
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<td>Magnetic Pulse Welding</td>
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<td>Carbon Fiber Reinforce Polymer</td>
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<td>Uniform Pressure Electromagnetic Actuator</td>
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REPLICATION OF RESULTS

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

CONSENT FOR PUBLICATION

Not applicable.

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