Experimental and numerical study on magnetic pulse welding to improving the life time of one-turn flat coil

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Abstract. The objective of this investigation was to obtain an improved understanding of magnetic pulse welding processes and the mechanisms of electromagnetic forces applied to a one-turn flat coil. Results of simple numerical investigation and experiments show that the electromagnetic forces on the middle part of the coil can be canceled out by loading the welded workpieces on both sides of the coil and can prevent coil deformation and improve its lifetime.

1. Introduction
Magnetic pulse welding (MPW) is an excellent and fast method for achieving similar or dissimilar metal joints. MPW uses magnetic pressure to drive the primary metal against the target metal, sweeping away surface contaminants while forcing intimate metal-to-metal contact, thereby producing a solid-state weld. Several technical research papers have reported on MPW. For example, Tamaki and Kojima [1] and Shribman et al. [2] used conventional MPW with a solenoid coil for joining tubular parts and investigated its features. Aizawa et al. [3] studied the applicability and the potential of MPW for joining several different aluminum alloys and steel sheets using a one-turn flat coil, which is a new solution for application to automotive and vehicle lightweight structures. Recently, Aizawa et al. [4] proposed a new MPW device with a newly designed one-turn flat coil and developed it for flexible printed circuit board lap joints.

MPW has been theorized and tested for several decades; however, optimization of MPW systems and improvements to the lifetime of the coil may play a major role in future developments of MPW systems for use in a wide range of industrial applications. A field shaper can be used in conventional MPW with a solenoid coil. In this case, the magnetic pressure that has to be reacted by the solenoid coil is smaller than the pressure that acts onto the workpiece, thereby significantly increasing the service life of the solenoid coil compared with a direct acting coil. However, the electromagnetic force arrangement in MPW with a one-turn flat coil is complicated and depends on the loading positions of the workpieces. The goal of our work was to investigate the effect of loading two sets of workpieces on both sides of the coil to decrease the total electromagnetic forces on the middle part of the coil. The ratio of the electromagnetic forces acting on the workpieces was also calculated numerically for several coil sizes for two cases (1) loading one set workpieces on one side of the coil, (2) loading two...
sets of workpieces on both sides of the coil and the results are compared with experimental results in the present paper.

2. Numerical modelling

The principle of MPW using a one-turn flat coil has been reported in previous work [3, 4]. In this section, details of the electromagnetic forces acting on the workpieces and the middle part of the coil are described by a simple model. Figure 1 shows a typical view of the coil and current and return current path with horizontal electromagnetic forces (\( \vec{g} \)) acting on the central part of the coil. It can be observed that the horizontal forces between the central current path and the two return current paths are nearly the same and that they are able to cancel each other out. Vertical electromagnetic forces appear on the coil and on the surface of the workpieces when discharge starts with loaded metal sheets.

Figure 2 shows the arrangement of the electromagnetic forces for two cases: (a) loading workpieces on only one side of the one-turn flat coil and (b) loading workpieces on both sides of the one-turn flat coil. When a high current is applied to the coil, then a high magnetic field \( \vec{B} \) is suddenly generated and penetrates the Al sheets. The eddy currents (current density \( \vec{i} \)) are produced because of this high magnetic field on the surface of the Al sheets (mainly on the base metal sheet). As a result, an electromagnetic force \( \vec{f} = \vec{i} \times \vec{B} \) acts mainly on the base metal sheet, which accelerates away from the coil and collides rapidly with the target metal sheet. Here, \( \vec{f}_{\text{coil}} \) is the force applied to the central part of the coil.

![Figure 1. Typical view of one-turn flat coil with forces and current direction without workpieces.](image1)

![Figure 2. Arrangement of electromagnetic forces: \( \vec{f}_{\text{coil}} \) acts on the central part of the coil, and \( \vec{f}_1 \) and \( \vec{f}_2 \) act on the Al sheets in two cases: (a) loading workpieces on only one side of the one-turn flat coil and (b) loading workpieces on both sides of the one-turn flat coil.](image2)
It is expected that the electromagnetic forces acting on the central part of the coil (\( f_{\text{coil}} \)) will be divided into two parts of opposing directions when loading two sets of workpieces on the coil sides (figure 2(b)), and these two parts are able to cancel each other out vertically. However, when loading one set of workpieces on the coil, a strong force (\( f_{\text{coil}} \rightarrow f \)) is applied to the coil and may damage and deform the coil structure. Conversely, \( f_2 \) is applied to the base metals and plays a major role in welding process, decrease in the case of (b). Its magnitude is smaller than that of \( f_1 \) for the same energy discharge.

3. Numerical calculation

Two forces, \( f_1 \) and \( f_2 \), were applied to the base metals (Al sheets) and play a major role in the welding process. They can be calculated by using a simple assumption for current density, as shown in figure 3. For calculation of the total magnetic field at point P in both cases (it can be assumed that point P is at a distance of \( c/10 \) from the base metal surface), we assume that the current and eddy current density are nearly same and they are following through the coil and base metal surface uniformly. The magnetic field at point P has three components. The first component is \( B_c \), which is produced by the main current on the central part of the coil, and \( B_1 \) and \( B_2 \), which are produced by eddy currents at the top and bottom side of the base metal. The dimensions \( a \), \( b \) and \( c \) represent the thickness, width, and insulator thickness, respectively, between the coil surface and base metal. The current density \( i \) [A/m] can be obtained by

\[
i = \frac{I}{2(a + b)}
\]

where \( I \) is total discharge current. In this model, the eddy current is assumed to flow uniformly in the range of coil width \( b \) on the base metal surface and its density is equal to \( ki \) [A/m]. The coefficient \( k \) is a specified value between equations (1) and (2). These magnetic fields \( B_c \), \( B_1 \), and \( B_2 \) can be given as follows:

\[
B_c = \frac{\mu l}{2\pi(a + b)} \left[ \tan^{-1} \frac{b}{2c} + \tan^{-1} \left( \frac{b}{2(a + c)} \right) \right] + \frac{1}{2} \ln \left[ \left( a + b \right) + \left( \frac{b}{2} \right)^2 / \left( c^2 + \left( \frac{b}{2} \right)^2 \right) \right],
\]

(1)

\[
B_1 = k \frac{\mu l}{2\pi(a + b)} \left[ \tan^{-1} \left( \frac{b}{2c/10} \right) \right],
\]

(2)

and

\[
B_2 = k \frac{\mu l}{2\pi(a + b)} \left[ \tan^{-1} \left( \frac{b}{2(a + 2c)} \right) \right].
\]

(3)

The value of “c” is smaller than “a” and “b” (c is insulator thickness in the order of 100 \( \mu \)m), and therefore, “c” is neglected in equations (1) and (3). We assume that \( B_c = B_1 \) when determining \( k \). The ratio of \( f_2 \) and \( f_1 \) (force on base metal for each cases) will be given by

\[
\frac{f_2}{f_1} \propto \frac{(2B_c - B_2)^2}{(2B_c)^2}.
\]

(4)

The numerical values of \( k \), \( B_c(T) \), and \( f_2/f_1 \) for some coil dimensions are summarized in table 1. The results of \( f_2/f_1 \) for \((a = 3, b = 5)\), \((a = 5, b = 3)\), and \((a = 8, b = 5)\) are compared with the maximum shearing strength values from the experimental results.
Figure 3. Distribution of current density in central part of coil and base metal for (a) workpieces loaded on one side of coil and (b) workpieces loaded on both sides of coil.

Table 1. Calculation results for ratio $f_2/f_1$ and $B_s(T)$.

| Coil Size(mm) | $a=2$ | $a=3$ | $a=4$ | $a=5$ | $a=6$ | $a=7$ | $a=8$ | $a=9$ |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|
| $C=0.1\text{mm}$ | $b=6$ | $b=5$ | $b=4$ | $b=3$ | $b=2$ | $b=1$ | $b=0$ | $b=-1$ |
| $k$           | 1.7   | 1.7   | 1.8   | 2.0   | 2.2   | 1.7   | 1.8   | 1.9   |
| $B_s(T)$      | 10.1  | 10.0  | 10.5  | 11.5  | 12.9  | 6.2   | 6.4   | 6.6   |
| $f_2/f_1$     | 0.49  | 0.62  | 0.74  | 0.83  | 0.90  | 0.63  | 0.70  | 0.76  |

4. Experimental procedure

A block diagram of the discharge system is shown in figure 4. It consists of a capacitor bank (C) and a spark gap switch (G) with an E-shaped one-turn flat coil. The capacitor bank is connected to the gap switch and the one-turn coil by a low inductance transmission line. Four capacitors with a total capacitance of 400 $\mu$F ($4 \times 100 \mu$F) were charged to between 1.5 and 4.5 kV for obtaining a discharge energy of 0.6–4 kJ. The typical maximum discharge current for 1.4 kJ discharge was measured by a Rogowski coil to be about 180 kA. The one-turn flat coil was made of a Cr–Cu alloy, and its inductance was measured to be about 0.039 $\mu$H. The main discharge current passed through the middle part of the coil, and the thickness and width of the central part of the coil were changed between 3 mm and 5 mm to confirm the numerical estimation. Commercial pure aluminum A1050 and A6016 aluminum alloy sheets were prepared to carry out the welding for A1050/A1050 and A6016/A6016 combinations. All Al sheets were 100 mm long, 100 mm wide, and 1.0 mm thick. The joining surfaces between the Al sheets were cleaned by ethanol before starting the welding. Insulating sheets of 0.1–0.3 mm thickness were loaded between the coil surface and the Al sheets. The welding characteristics can be improved by fixing the initial gap (1 mm) between two Al sheets [3]. After welding, the welded sample was divided into 10 pieces, which were then used in the tensile shearing strength test.

Figure 4. Block diagram of discharge system and appearance of discharge circuit.
5. Experimental results and discussion

5.1. Tensile shear test

Welded samples were investigated on a standard tensile shear testing machine at a test rate of 10 mm/min. Comparisons of shearing load for two-side and one-side welding were obtained by preparing several welded samples in various experiments with different coils and different dimensions of the middle part of the coil. The tensile shear test results for three coils of different sizes are summarized in figure 5. A1050 was used for preparing welded samples with lower energy discharges, and A6061 alloy was used for investigating higher energy discharges. The comparison shows that the average of maximum shearing strength is nearly the same in both cases, but the minimum discharge energy for achieving a good joint when loading samples on both sides of the coil was about 1.5 times higher than that in the case of one-side loading. If we assume that the ratio of \( f_2 \) and \( f_1 \) is directly related to the average of the maximum shearing strength of the interface joint in both cases, then the experimental results, shown in the graphs in figure 5, also confirm the numerical estimation, qualitatively.

![Graphs showing tensile shearing strength versus bank energy for two-side and one-side loading cases.](image)

Figure 5. Comparison of tensile shearing strength versus bank energy for two-side and one-side loading cases. (a) (A1050 with 1 mm thickness); central part of coil size: 3 mm thick, 5 mm wide, (b) (A1050 with 1 mm thickness); central part of coil size: 5 mm thick, 3 mm wide and (c) (A6061 with 1 mm thickness) 8 mm thick, 5 mm wide.
5.2. Coil deformation
The deformation of the middle part of the coil was measured by a standard surface roughness measuring instrument (figure 6(a)). After each discharge, the deformation of the middle part of the coil was measured, and before the next measurement, the deformation was corrected by generating a discharge without any samples. The deformation of the middle part of the coil was low for when loading samples on both sides of the coil for low energy discharge (less than 2 kJ for A1050/A1050 combination). However, the deformation of the middle part of the coil was increased by increasing the discharge energy when loading samples on one side of the coil. The aluminum alloy A6061 sheet with thickness of 1 mm was used to further investigate coil deformation over a wide range (1 to 4 kJ) of bank energy discharges. The middle part of the coil was 8 mm thick and 5 mm wide in this experiment. Figure 6(b) shows a comparison of the deformation ratio of the middle part of the coil (ratio of deformation and coil thickness) versus the bank energy for two-side and one-side loading.

The deformation ratio was obtained by the average value measured at the three points along the middle part of the coil. The maximum deformation was about 0.02 mm in the case of two-side sample loading, and it was about 0.3 mm in the case of one-side sample loading. Reproducibility of the deformation values was poor, but the difference between the two cases remained considerable.

Figure 6. (a) Standard surface roughness measuring instrument and (b) comparison of middle part of coil deformation ratio (ratio of deformation and coil thickness) versus bank energy for two-side and one-side loading cases (A6061/A6061; sample thickness 1 mm; coil: a = 8 mm; b = 5 mm).

6. Conclusions
In this work, the MPW processes and mechanisms of electromagnetic force were investigated for two types of loading, and the main results are summarized as follows. (1) The energy required for welding workpieces of the same materials loaded on both sides of the coil was approximately 1.5 times higher than that required for welding loaded workpieces on one side of the coil. (2) The energy required for welding one pair of workpieces on both sides of the coil was about 3/4 that required for welding the workpieces on one side of the coil. (3) The coil deformation in the case of loading on both sides of the coil was about 1/10 or less than that in the case of loading on one side of the coil. Therefore, loading the workpieces on both sides of the coil can improve the energy efficiency and the coil lifetime significantly.
Acknowledgments
The authors wish to express their thanks to Prof. K. Okagawa and Dr. M. Ishibashi of Tokyo Metropolitan College of Industrial Technology for cooperation on coil roughness measurements.

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