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Magnetic Pulse Welding of Al/Cu Sheets using 6-Turn Flat Coil

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A high pulse current (e.g. peak 150-200 kA) is discharged through a one-turn flat coil which is usually used for magnetic pulse welding of sheet metals. Little attention has been paid to decrease the current. In this study the current was decreased using a 6-turn flat coil and the weldability of dissimilar sheet metals was checked. The 6-turn coil could generate the magnetic flux of the same value by the current of about 1/6 in comparison with the one-turn flat coil. Al/Cu sheets were overlapped with a gap and fixed on the 6-turn coil. When a magnetic flux was suddenly generated around the coil, eddy currents were induced in the sheets. Electromagnetic force acted on the Al sheet nearer the coil. This sheet was collided to the Cu sheet and welded. The peak current required for this welding was 25 kA at the discharge energy of 0.6 kJ.

Introduction

In magnetic pulse welding (MPW), electromagnetic forces are used to weld metal work-pieces. For a long time, the MPW method has been used for welding tubular work-pieces [1,2]. Recently, this method is applied to flat work-pieces [3-5]. The most common configurations consist of a lap joint of similar or dissimilar metals. The mechanism and features of MPW are considerably well known. Its technique is based on discharging a high pulse current through a coil to produce electromagnetic forces. The coil shape is chosen to become strong in the electromagnetic coupling between the coil and the work-pieces. A solenoid coil (usually a multi-turn coil) is used for the tubular work-pieces. On the other hand, a one-turn flat coil is mainly used for the flat work-pieces.

The flat work-pieces are overlapped sheet metals, which are usually fixed on the insulated E-shaped one-turn flat coil [3,4]. The peak discharge current for the welding is, for examples, 150-200 kA. About the improvement of such a high current, MPW of sheet metals has not been studied enough. Little attention has been paid to the MPW technique using a multi-turn flat coil. This flat coil had difficulty in design and manufacture in comparison with the multi-turn solenoid coil. A few examples of the multi-turn flat coil have been reported in Japan [6,7].

The objective of this study is to decrease the high current technically. The E-shaped 6-turn flat coil was adopted to decrease the current and the weldability of dissimilar sheet metals was tested. The current for the welding decreased to about 1/6. The properties of the Al/Cu sheets welded by the 6-turn flat coil were similar to the case of the one-turn flat coil. The collision speed of the Al sheet to the Cu sheet was calculated and the weld interfaces were observed. The deformation of the coil after the welding was also checked.

Experimental procedures

Figure 1 is a sketch of the E-shaped 6-turn flat coil for MPW. The coil comprises six pieces of E-shaped metal plates which are electrically insulated and are laminated. The discharge current flows into the narrow central part of the plate No.1 upward and flows out from the two wide outside parts downward. The divided currents join at the lower parts of the plate No.1. The joined current flows again into the central part of the plate No.2. The discharge current flows through each central part in series and does six turns. Each central part of the plates is just piled up with the same width. A high-density magnetic flux is generated around the piled central part as the 6-turn flat coil. Therefore, this coil can generate the magnetic flux of the same value by the current of about 1/6 in comparison with the one-turn flat coil if the coil-design and other conditions are suitable.

The sheet metals (Al/Cu) for the welding are fixed on the 6-turn coil like Fig. 2. The lower Al sheets are insulated in a DC manner from the coil, but there is electromagnetic coupling between them. When the discharge current flows into the coil, the high-density magnetic flux is suddenly generated around the central part. The flux intersects the lower Al sheet and eddy currents are induced electromagnetically in the skin of the Al sheet. The eddy currents near the central part flow in opposite direction to the discharge current of the central part. As a result, the electromagnetic force \mathbf{f} acts on the Al sheet (Fig. 2). The Al sheet is accelerated upward and collides with



Fig.1 Sketch of 6-turn flat coil.

Fig.2 Fixation of coil and Al/Cu sheets.

the upper Cu sheet at very high speed. The Al/Cu sheets will be welded along the central part by the decreased discharge current of about 1/6. The type of the welding is such a seam welding.

The electromagnetic force f to act on the Al sheet is proportional to the square of the discharge current. The discharge current is proportional to the magnetic flux density. The details of these are shown elsewhere [4].

Experimental apparatus and materials

The discharge system consisted of the capacitor bank, a discharge switch, the 6-turn flat coil and others. The capacitor bank (capacitance C=24 μ F) consisted of four capacitors of 6 μ F in parallel. The bank was connected to the discharge switch and the coil by low inductance transmission lines. The charged energy *E* of the bank was 0.6 kJ. When the switch was closed, the discharge current suddenly flowed through the coil and the part of energy *E* moved to the coil as magnetic energy. The welding process was finished in one shot of the discharge.

The coil was mainly made by six E-shaped plates (0.3 mm thick) of Cu alloy. The narrow central part of each plate was 5 mm wide and 110 mm long. The thickness as the 6-turn flat coil was approximately 3 mm including the insulators and about the same as that of the conventional one turn flat coil. Each insulator was polyimide of about 0.1 mm thick. Figure 3 shows the appearance of the 6-turn coil consisting of the plates which made gaps for photography without the insulators. The inductance of the 6-turn coil was about 1.3 μ H and larger enough than the inductance to exist (or remain) in the discharge circuit except the coil. The energy *E* will move more to the 6-turn coil as magnetic energy in comparison with the one-turn coil of smaller inductance.



Fig.3 Appearance of 6-turn flat coil, (a) plate No.1 side and (b) plate No.6 side.



Fig.4 Block diagram of discharge and measuring system.

Fig.5 Current and collision time signals.

The Al (1050) and Cu (1220) sheets were 100 mm long, 100 mm wide and 0.5 mm thick. The Al/Cu sheets were overlapped 50 mm in length with the gap of 1.0 mm and fixed on the coil covered by the thin insulator such as Fig.2. The discharge current signal and a collision time signal of the Al/Cu sheets were obtained by using a measuring system as shown in Fig.4. The interfaces of welded Al/Cu sheets were observed by microscopes.

Experimental results

Typical discharge current and collision time signals are shown in Fig. 5. The damping and oscillating current flowed through the coil for duration of about 100 μ s. In measurement the oscillating period was 36 μ s, and so the skin depth was 0.5 mm for the Al sheet. The peak discharge current was 25 kA at the discharge energy of 0.6 kJ. The sheets collided in around the time for the peak current and after 9.5 μ s from the start of the current. The collision speed when the sheets collided was calculated roughly with 210 m/s.

Figure 6 shows a typical appearance of the welded Al/Cu sheets taken from the Al sheet side. A part of the Al sheet deformed toward the Cu sheet along the narrow central part. The weld zones (usually two seams) were in the deformed region which was 100 mm in length to the longitudinal direction and about 10 mm in width direction. The welded sheets were cut and polished for the interfacial observation.

Figure 7 shows a cross sectional appearance of the welded Al/Cu sheets (or weld interface) at the deformed region. Two weld zones marked by arrows (\downarrow) and a middle clearance (non-weld zone) were seen in Fig. 7. This result was similar to the result using the one-turn flat coil [3-5]. Figure 8 is a typical optical micrograph of the interface at the one weld zone and Fig.9 a SEM image of the same interface. Wavy pattern morphology was seen in the weld interfaces as shown in Fig. 9. Such morphology was also seen in the case of the one-turn flat coil [3-5].

Figure 10 shows the appearance of the coil without the insulators after the welding experiments of about 40 times. Each coil plate and each insulator were not damaged by these experiments. The deformation such as wrinkles was



Fig.6 Appearance of welded Al/Cu sheets.



Fig.7 Cross sectional appearance of welded Al/Cu sheets.





Fig.8 Optical micrograph of weld interface at one weld zone.

Fig.9 SEM image of weld interface at one weld zone.



Fig.10 Appearance of 6-turn flat coil after experiments of about 40 times, (a) plate No.1 side and (b) plate No.6 side. Clear deformations occurred in parts of white line circles.

seen partially in each coil plate. The relatively clear deformation occurred in the parts of white line circles (Fig. 10). It was possible to continue the experiments with this coil, but the coil was destroyed before long.

Conclusions

We found that the peak discharge current required for MPW of sheet metals was about 25 kA by using the E-shaped 6-turn flat coil. The welding results with this coil were similar with the case of the one-turn flat coil. The welded Al/Cu interface indicated wave interface morphology like explosive welding. The deformation (or damage) of the coil was also shown. Future work will need to improve the coil life and to increase the coil turns.

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