Review Paper

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Review of magnetic pulse welding

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Abstract

Magnetic pulse welding(MPW) is a solid state welding process that is accomplished by a magnetic pulse causing a high-velocity impact on two materials, resulting in a true metallurgical bond. One of the great advantages of MPW is that it is suitable for joining dissimilar metals. No heat affected zones are created because of the negligible heating and the clean surfaces formation that is a consequence of the jet and the metal is not degraded. Also, compared to other general welding processes, this process leads to only a low formation of brittle intermetallic compounds However, although this process has many advantages its application to industrial fields has so far been very low. Therefore, in this study we are presenting the principles, apparatus and application of MPW for application the industrial fields.

Key Words : Magnetic pulse welding, Dissimilar metals welding, Electromagnetic force

1. Introduction

The car industry is currently working to accept the conflicting requirements of both environmental legislation and customer demand for high performance and safety by developing a light-weight vehicle[1]. In order to meet these very different goals, light weight materials such as aluminum and magnesium has been applied for automotive components. Especially, the development of aluminum space frames for automotive body structures has been carried out in recent years[2]. However, when only lightweight materials are used in automotive body structures, the materials cannot satisfy the required intensity and strength properties, also it is imperative to weld lightweight materials to currently used materials. Accordingly, it has become required to study the welding of dissimilar metals that have different material properties. Welding processes, such as the existing process of fusion welding by heat generally causes not only defects such as solidification, cracking, porosity and oxidation but also transformation and corrosion. Therefore, the magnetic pulse welding process as a kind of solid-state welding process has been focused on these days[3,4,5].

Magnetic pulse welding (MPW) is a solid state welding process that is accomplished by an electromagnetic force causing a high-velocity impact on two materials, resulting in a true metallurgical bond. MPW is not a recently developed welding process. It was developed for military applications such as the joining of projectiles to artillery shell castings[5,6]. in the former Soviet Union 40 years ago. The strong advantages of MPW are its ability to join dissimilar materials and its potential application to surface treatment materials. Furthermore, MPW is an environment-friendly process that can be employed to manufacture high quality products without the use of gas, filler metals or lubricants, all of which are sources of environmental pollution generated during welding. As no heat is applied to the material, defects do not occur and a high quality weldment can be obtained. For this reason, this process can be diversely applied across a broad range of industries. including the electric/electronic, automobile and aerospace industries this process, due to its high productivity and high quality, is being applied to industrial fields in order to obtain economic benefits[7,8]. Therefore, many researchers have been focusing on the development of the MPW process and on prototypes. Especially, Ohio State University And the IUL(Institute of Forming Technology and Lightweight Construction) of TU Dortmund University

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have led the development in experiments and simulations. Also, numerous research institutes such as KITECH(Korea Institute of Industry technology) and Fraunhofer have been carrying out research on process optimization. In contrast, only a few applications have been applied for industrial fields. Therefore, the objective of this paper is to report the principles of MPW the overall MPW system, and applications for commercialization and technology diffusion in industrial fields.

2. Magnetic pulse welding

2.1 Principales

When charged high electrical energy in capacitor banks is discharged to a working coil by a discharging switch, the result of this current discharge (i_1), which is a highly damped sinusoidal wave, a transient magnetic field (H_z) that is produced in the working coil and that penetrates into the outer material, placed in its vicinity as shown in Fig. 1. This transient magnetic field induces eddy currents (i_2) with opposite direction in the outer material. As two opposite magnetic field repel each other, the repulsive forces, called electromagnetic force(F_r), lead to the outer mateial flying away and consequently to a collision between the two materials. The electromagnetic force that is applied to the outer material is described by the following equation:[5)]

$$F_r = \frac{B_z^2}{(2\mu_0)} = \frac{\mu_0 H_z^2}{2} \tag{1}$$

The end point of the outer material that is applied to the high electromagnetic force starts to collide with the inner material as shown in Fig. 2(b) Then, the two materials weld like a flowing liquid, as shown in Fig. 2(c)[6)]. This dynamic behavior of the materials leads

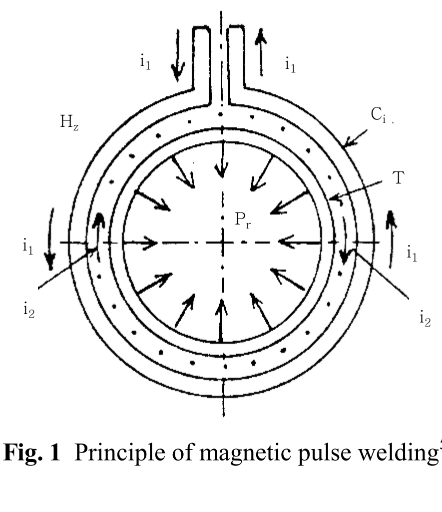


Fig. 1 Principle of magnetic pulse welding[5)]

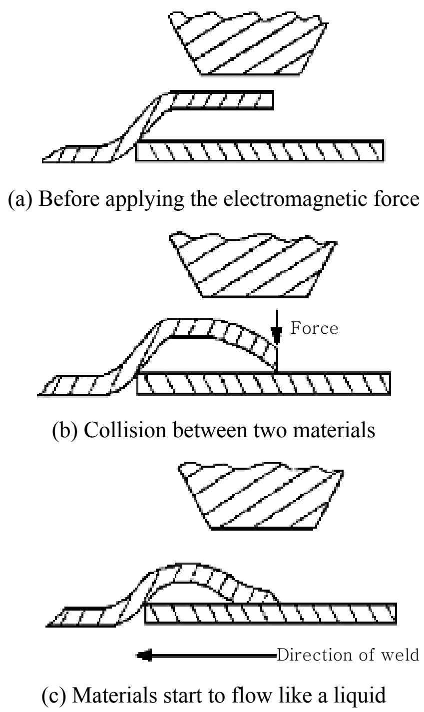


Fig. 2 Materials deformation and welding[6)]

them to generate interfacial waves that are formed by the Kelvin–Helmholtz instability mechanism[7)].

2.2 Process parameters

In order to ensure the quality of the weldment as well as to ensure the work efficacy of the MPW process, it is necessary to understand the effects of the process parameters. To achieve a successful weldment, the design of the velocity of impact (V_{impact}) and angle (θ_{impact}) are important as shown in Fig.3. The impact velocity is related to both the pressure and the kinetic energy used to accelerate the outer material, the impact velocity is determined by the specifications of the apparatus. The angle between the materials can be determined based on the geometry of the materials. Therefore, the process parameters that affect the MPW process include the apparatus parameters such as charged electrical energy, frequency of discharge current, and inductance of the coil, as well as the material parameters such as material type, dimensions of the materials, gap between the materials, electric conductivity, strength, elongation, and surface conditions. In particular, to obtain a high quality weldment using the same apparatus and materials, it is very important to select optimal values for the charged electrical energy as the electromagnetic force, the gap between the specimens and the dimensions of the materials. The collision of the materials when using optimal process parameters creates a jet and this causes the perfect ejection of air and oxides

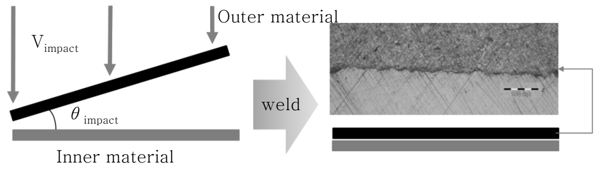
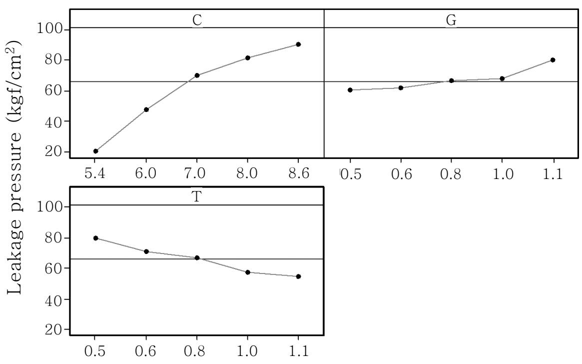
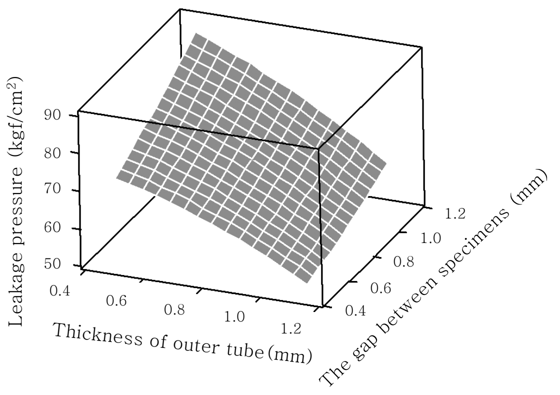


Fig. 3 Description of the weldment



(a) Main effect of plot on response variable



(b) Surface plot of response variable

Fig. 4 Analysis of process parameters using D.O.E[1)]

from the surfaces of the materials. The emission of the jet results in cleaned surfaces, free of oxides or other contaminates, allowing the impact at high velocity to overcome the forces between the atoms of the materials and to bring the atoms together with in such intensity that the electrons can be shared between the two materials, creating a weldment[6-8)].

Theoretical analysis of the MPW process was started by Spitz, B.T[9)], P. Zhang[10)], and D. Dudkoet. et. al[6)] and was used to describe the relations between the process parameters and the weldment. Hokari et. al[5)] reported on the optimal ranges of the process parameters for successful joining of aluminum and copper or aluminum and steel. By observing cross sections after welding aluminum and steel in different process conditions, V. Shribman[11)] analyzed the effect of the process parameters on a joint in terms of its metallurgical aspects. Recently, Shim[1)] studied the effect of process variables on the Al/steel joint quality using an experiment design method and regression equation, as shown in Fig. 4.

3. Apparatus for MPW

3.1 Capacitor bank

Generally, the MPW apparatus consists of capacitor banks for charging to extreme levels of energy and a working coil to discharge that energy as shown in Fig 5.

The electromagnetic pressure used to set the outer material into motion, P, is determined by the design for the total apparatus for creating the magnetic pulse and is described by:[9)]

$$P=\mu_0 K^2 n^2 U^2 C\frac{\sin^2(\omega t(e^{-Rt/L}))}{2L\lambda^2} \qquad (2)$$

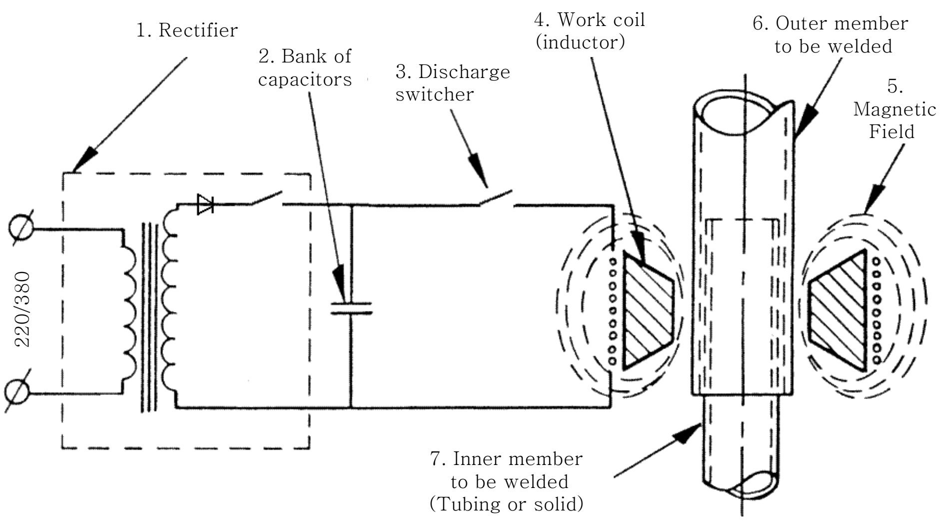
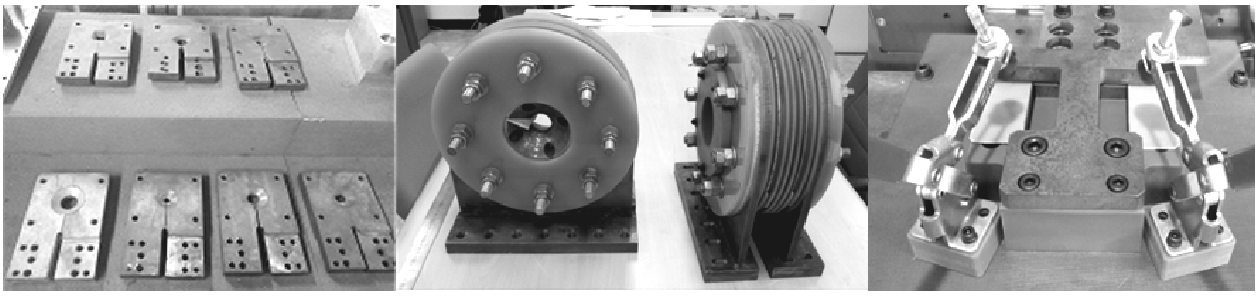


Fig. 5 System of magnetic pulse welding[5)]



(a) One-turn working coil (b) Multi-turn working coil (c) Plate coil

Fig. 6 Working coil

In order to generate the requisite high electromagnetic pressure, capacitors with extremely low self-inductance are used these devices can store charges up to a certain maximum level that is determined by the operator. This system creates a high current pulse in the work coil within 100 microseconds[6]. For agile discharge of the high electrical energy, a high current discharge switcher was employed on the magnetic pulse power sources so that the energy expenditure would be very low.

3.2 Working coil

The development of the working coil is directly related to the weldment quality, and so the development of the working coil is very important in the MPW apparatus. However, theoretical analysis for the development of optimum working coils considering various factors has not yet been performed. Nevertheless generally the considered factors can be classified into shape and mechanical and electrical properties of the material. The types of working coil are generally classified into a compression coil, expansion coil and plate coil. A compression coil is a solenoid type coil surrounding materials that are welded from the outside to the inside. An expansion coil is inserted inside materials and welded from the inside to the outside. A plate coil, which located on and under the materials is employed in plate welding[3]. The material of the working coil should allow for electrical and mechanical properties such as conductivity to prevent damage to the condenser due to the duration of the magnetic field or sudden discharge; it should also provide strength to prevent the repulsive force during welding. Therefore, copper, aluminum and beryllium-copper have been considered as materials for the working coil, as shown in Table 1. Fig. 6 shows the various types of working coils that have been developed using various materials for tubular and plate welding at KITECH[12].

Two companies, PST Products and WELMATE Ceo., Ltd,, working independently, are leading the developments of MPW apparatuses recently. Fig. 7 shows the MPW system, including capacitor banks; system has a maximum charging energy of 60kJ, working coils and a 6-axis robot that is manufactured by WELMATE CO., LTD.

Table 1 Mechanical and electrical properties of working coil

Material	Hardness (Vickers)	Electrical Resistivity (ohm-m)	Permeability (μ)
Al 6061	75	4.32e-8	1
Cu1220	50	1.70e-8	1
Becu17000	90	2.94e-8	1

Fig. 7 Apparatus of magnetic pulse welding

4. Applications of MPW

The MPW process only uses the electromagnetic force, and so there is no effect of heat during the process. Therefore, this process can be applied for the welding of dissimilar materials such as aluminum/steel, aluminum/copper and so on. Moreover, it can be applied for the surface treatment of materials such as anodized aluminum and vinyl coated materials. Although MPW distinct advantages, few applications have yet been developed in industrial fields. In fact, MPW has been available for about 40 years, but its use has been very limited up till now. However, the development of

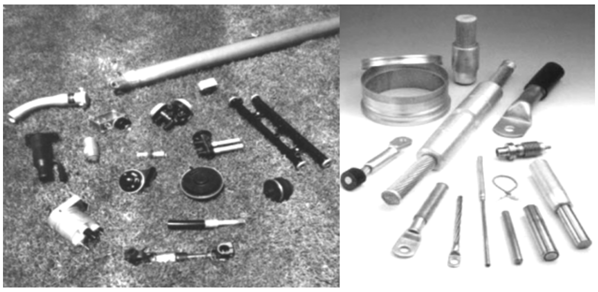


Fig. 8 Application of the magnetic pulse welding[13)]

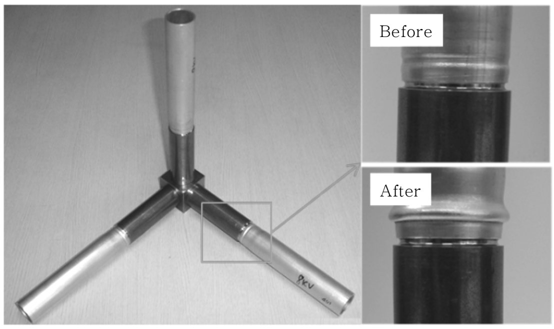


Fig. 9 Al/Steel weldment

an apparatus for magnetic pulse welding at a commercial level will lead to application of this technology to industrial fields, and as such the market is expected to grow quickly[9,11,13-18)]. Especially, MPW can be applied to the automotive industry and to electronic devices as shown in Fig. 8, it can be used to replace the currently-utilized fusion welding processes such as brazing, friction welding, roll bonding and explosive welding[19,20)].

For application to industrial fields, dissimilar metal welding which considers the required quality of the final product, such as aluminum/steel or aluminum/copper was tried a few years ago. In the automobile industry, It is essential to convert from steel to lightweight materials, and so to development of lightweight vehicle bodies and components has been carried out in the 21st century. Fig. 9 shows a developed aluminum/steel weldment and the results of a compression test for certain automotive bodies[12,21)]. In order to apply this processing to automotive components, the development of a lightweight driveshaft that can join an aluminum tube and a steel yoke was conducted, with results as shown in Fig. 10.

In addition, aluminum has been focused on as a material to replace copper in tubes for refrigeration cycles, its application is being expanded to home appliances. In order to apply dissimilar tube joints for the refrigeration cycle, an Al/Cu weldment was developed, as shown in Fig. 11(a). The developed Al/Cu weldment was evaluated according to He gas leakage it was also subject to a water leakage test and an analysis of the interface of weldment. Figs. 11(b), (c) show the results of the evaluation of the Al/Cu weldment. There is no leakage of the weldment and Al tube eventually burst due to high hydraulic pressure Awave pattern was observed on the interface of the Al/Cu weldment.

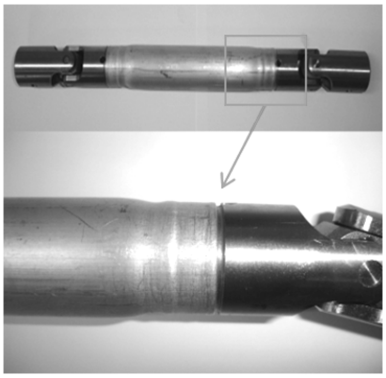
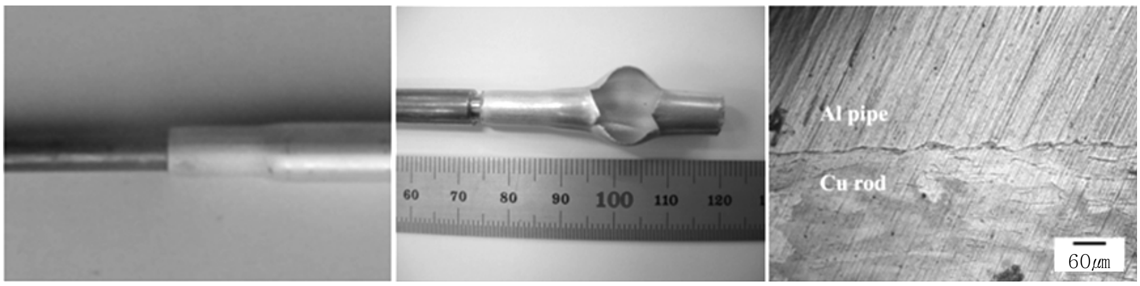


Fig. 10 Al/Steel lightweight drive shaft

Table 2 presents various material combinations that have been successfully welded. As yet unexplored though, is possibility of welding recently developed ultra high strength steels. Moreover, electromagnetic force can be applied to forming, punching, cutting, crimping and perforating process[9, 11,13,21)].

5. Conclusions

Magnetic pulse welding process (MPW) is one of the useful welding processes of the dissimilar sheet and



(a) Al/Cu weldment (b) Results of leakage test (c) Wavy interface

Fig. 11 Results of Al/Cu weldment evaluation

Table 2 Material combinations for successfully magnetic pulse welding[9,11,13)]

	Mg	steel	Ni	Ti	SS	Zr	Mo	Brass	Cu	Al
Al	●	●	●	●	●	●	●	●	●	●
Cu	●	●	●	●	●	●	●	●	●	●
Brass								●	●	●
Mg	●									●
Steel		●			●					●
Mo							●			
Zr						●				
SS			●	●	●					
Ni			●	●	●					

tubular materials joining, because this process only use the electromagnetic force through electromagnetic interaction between welding coil and materials. Because of its numerous advantages, MPW can be applied to a variety of applications to reduce manufacturing costs and achieve higher weld quality, it can also enhance productivity. Nevertheless, the welding industry has not paid much attention to this process. For application to industrial fields, the development of a process design and of an MPW apparatus that can considers the needs of the industry and the development of prototypes that can ensure the required quality and efficiency of welding, will have to be carried out as soon as possible.

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