ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015

Development of Aluminum Small Digital Electronics Cases Using Magnetic Pulse Forming Process

Ji-Yeon Shim, Bong-Yong Kang*

Abstract*— The aluminum alloys has high strength-to-weight ratio and good corrosion resistance, but the low formability of aluminum alloys limited their use in some products at high temperature. Therefore, it need to develop the effective forming process which is improved the formability of aluminum alloys by high velocity for expanding use in many areas. Magnetic pulse forming is a process to form the metal with high speed within 200μs using a magnetic field of high strength. This process is formed by electromagnetic force which occurs by electromagnetic phenomena between forming coil and work piece. Therefore, the objective of this study is to develop magnetic pulse forming process to be applied to industrial sites and to manufacture the aluminum alloy prototype of small-sized digital electronic product. In order to carry out this, bar-type and helical-type forming coil were developed for magnetic pulse forming process in this study. Thorough the analysis of deformation phenomenon, magnetic pulse forming process which is used the bar-type forming coil with punch was developed for industrial site. Manufactured aluminum alloy prototype case using developed magnetic pulse process can be expected to apply small-sized digital electronic product such as cellular phone, digital camera and notebook

Index Terms— **Aluminum alloy; Electromagnetic force; High speed forming; Small digital electronics cases.**

I. INTRODUCTION

The developments in the aluminum industry, improving the mechanical properties of the aluminum alloys by adding various alloying elements increased the application area of these alloys in automotive and electronics industries. [1] The metal case for a small-sized digital electronic product is generally a part in which the needs of customers who regard the design as important are reflected as they are in electronics industry. Especially, the durability of the case became important following its recent simplicity and exclusivity of case is required, the use of right-weight materials such as aluminum alloys and magnesium is being examined.

Typical aluminum alloys forming processes are bending, deep drawing, and stretching. If a doubly curved product must be made from a metal sheet, the deep drawing process or the stretching process is used.[1] However, aluminum alloys are the low-formability materials, which the aluminum alloys has low total elongation and low bending elongation, a yardstick for bending workability, it is very difficult to forming process in room temperature.[2-4]

Magnetic pulse forming is one of high velocity forming process for forming the low-formability materials. This process is done without physical contact since electromagnetic force applies on the work piece through the electromagnetic interaction between the processing material and the coils. Therefore, this method may be a kind of environment-friendly process that does not require lubrication, etc., as in the case of conventional press forming. This also enables saving on the manufacturing cost because lower-part die may be unnecessary depending on the process. In addition, it is a highly efficient forming process that can be possible the precision forming by design of the shapes of forming coils. Furthermore, since forming is completed at room temperature, the mechanical property of work piece is maintained, so this method can be applied to various forming processes including pipe expansion/compression and sheet forming. Compared with conventional press forming, magnetic pulse forming has the advantages of high quality, environment-friendliness, and high productivity.

The development of the forming process using electromagnetic force was started in the US in the 1960s. The process has been expanded from forming process including pipe expansion/compression to forming process to be applied to airplanes, automobiles, and small home appliance cases. Magnetic pulse forming has so far been studied process analysis not only to promote increased formability, suppress wrinkling and reduced spring back, but also to improve the surface finish by Daehn et al. [4] and Balanetihiram et al. [5] The US's Ohio State Univ., China's Wuhan National High Magnetic Field Center, and Germany's Dortmund Univ., and IUL(Institute of Forming Technology and Lightweight Construction) study on the development of magnet pulse forming apparatuses and effect of process parameters on this forming process.

Especially, studies on aluminum forming process using electromagnetic force have been conducted through experimental works and numerical analyses. Takatsu et al.[6] described the basic equations to simulate the electromagnetic free bulging of a sheet. Work by Fenton and Daehn[7-8] demonstrated that a two-dimensional Arbitary Lagrangian Eularian(ALE) finite difference code has accurately been employed to predict the dynamics of the magnetic pulse forming process. With the development of commercial finite element codes, another approach has been proposed by Oliveira et al.[9] which developed a simple 'loosely coupled' model to simulate aluminum alloy sheet forming. The loosely coupled model allows accurate simulations of the magnetic pulse forming process. In that study, they investigated dynamic behavior of aluminum alloy sheet with double spiral coil and then, major and minor engineering strains of work piece predicted using the numerical FE-model. Also Bendjima[10] considered the electromagnetic force due to motion of the work piece utilizing two-dimensional finite element techniques to model the transient phenomena in magnetic pulse forming. As experimental works, Imbert et al.[11] examined the effect between tool and sheet interaction on damage evolution in magnetic pulse forming through free-form and conical die experiments. L. Qiu et. al.[12], reported a study on the dynamic behavior of aluminum depending on the forming speed through numerical analyses. M. Kamal et. al.[13] attempted to develop cellular phone cases using magnetic pulse forming. However, this technology is multi-step forming process using two or more forming coils and cannot be applied to the industrial site where productivity is considered. Therefore, the objective of this study is to develop magnetic pulse forming process to be applied to industrial sites and to manufacture the prototype aluminum case for small-sized digital electronic product. In order to achieve this objective, two-type forming coil was developed for magnetic pulse forming process and then depth of deformation on work piece which use two-type forming coil in forming process was analyzed for developing the magnetic pulse forming process for applying the industrial site.

II. MAGNETIC PULSE FORMING

A. Principle and apparatus

Magnetic pulse forming is the technology for forming the metal at high speed using electric energy. Accordingly, sufficient electric energy for the plastic deformation of work piece is required. In general, high voltage for sufficient electric energy required is discharged in a short time to form a high magnetic field instantaneously.[13] Therefore, a magnetic pulse forming apparatus consists of an magnetic pulse power source having high capacitance, forming coil, one-side die, and press unit.

The magnetic pulse power source generates the high-voltage electric energy to the forming coil, and the magnetic pulse power source depends on the capacity of energy storage. When the capacitor is completely charged, it is instantaneously discharged at high voltage through an ignitron switch. The magnetic pulse power source is designed to have low inductance so that the energy is transmitted fully to forming coil in magnetic pulse forming process. Forming is completed by electromagnetic force when the forming coil generates high magnetic fields instantaneously between the work piece and forming coil as shown Fig. 1.

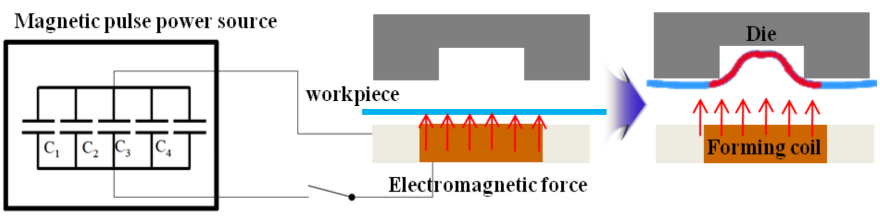


Fig. 1 Principle of MPF process

Since electromagnetic force acts on the forming material within tens of us, electromagnetic force should not be less than the yield strength for successful forming. In terms of the gap between a forming coil and a workpiece in relation to forming efficiency, high electromagnetic force generally is generated when the gap is small. The forming coil is designed in different shapes and dimensions by the final shapes of products and purposes. A theoretical analysis for designing high-efficiency forming coil considering various factors has yet to be established, but the general factors to be considered are the electric, mechanical properties, dimensions and shapes of material.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015
The materials of forming coil are limited to metals having low resistivity to minimize the loss caused by adiabatic heating during the forming process. Also, the materials should have sufficient mechanical strength and mass to keep stability and withstand the repulsive force during the forming process. Beryllium copper, aluminum alloy and copper are usually used due to its high mechanical and electrical properties such as yield strength and low electric resistance as shown Table 1.

Table 1. Mechanical and electrical properties for forming coil.

Material	Hardness(Vickers)	Electrical Resistivity(ohm-m)	Permeability(u)
Al 6061	75	4.32e-8	1
Cu12200	50	1.70e-8	1
Becu17000	90	2.94e-8	1

The shapes of forming coils are classified depending on the winding turns and method, distribution of electromagnetic force to the work piece and discharge time are determined this shapes. Therefore, the workpiece shows different dynamic behaviors depending on the shapes of the forming coils. Thus, the forming coils should be designed considering the shapes of the products to be produced.

Table 2. Developed two-type forming coil for this study

Forming coil	Frequency(kHz)	Capacitance(uF)	Inductance(uH)
Bar-type	16	480	0.2
Helical-type	6.2	480	1.3

As shown in Fig. 2, magnetic pulse forming apparatus which manufactured by WELMATE CO.,LTD. was employed for this study. This apparatus consists of a magnetic pulse power source with a maximum charging energy of 24kJ, a forming coil and a die. The gap between forming coil and work piece was set about 1mm for considering the insulation for electric troubles and convenience in setting the work piece before/after forming.

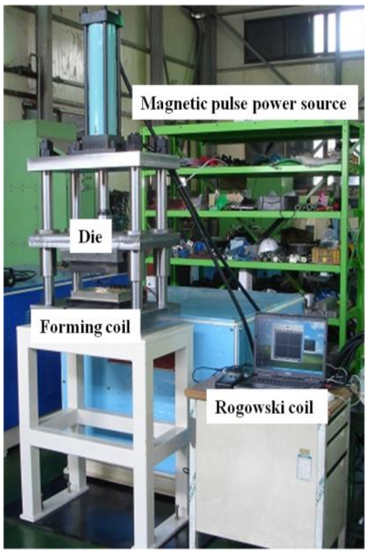


Fig. 2 magnetic pulse forming apparatus

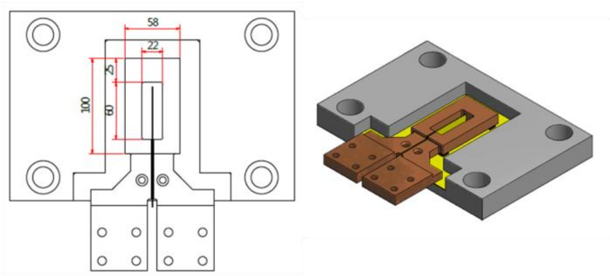
The work piece for forming was employed 0.5mm Al 5051-O having the yield strength of 193MPa. Rogowski coil for measuring the discharge current and time was set the connection part between magnetic pulse power source and forming coil as shown in Fig. 3. The Ro-gowski coil can measure the current linearly from the low-current area to the high-current area using mutual inductance. Moreover, it can measure the current in a wide frequency range. The depth of deformation on work piece according to the shape of forming coil was precisely measured by 3D scanning after forming.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015

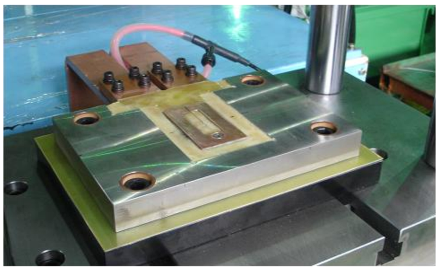
Fig. 3 Rogowski coil for measuring the discharged current and time

B. Bar-type forming coil

As described above, high electric energy should be released to generate a high magnetic field between a forming coil and a forming material. For this, the inductance of the forming coil should be minimized. A bar-type forming coil having inductance of 0.2uH was designed using auto CAD and inverter as shown in Fig. 4 (a) and then manufactured forming coil using copper was insulated with epoxy and was connected with an magnetic pulse power source Fig. 4(b). Fig. 5 shows the discharged wave form by Rogowski coil. When bar-type forming coil used in magnetic pulse forming process, the damped sinusoidal waveform was measured and the discharge time was about 60us, and forming was completed at 15us when flow the peck discharge current on forming coil.



(a) Design of forming coil



(b) Manufacturing the forming coil
Fig. 4 Bar-type forming coil for this study

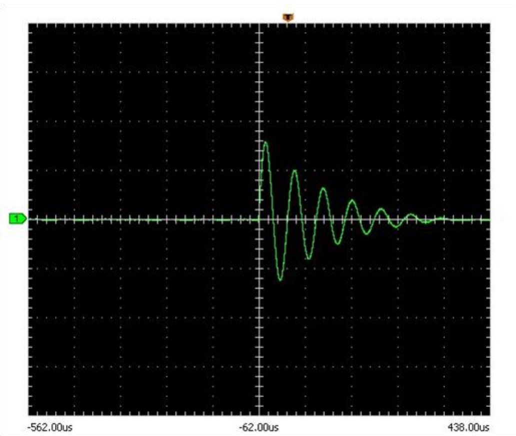


Fig. 5 Discharge waveform (Y: 20v/div, X: 100us/div)

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015

Peak discharge currents of about 3kV, 4kV, 5kV, 6kV were measured as 147kA, 175kA, 203kA, and 231kA as shown in Table

Table 3. Measured peak voltage and current

Charged voltage(kV)	Charged Energy(kJ)	Measured peak voltage (V)	Measured peak current(kA)
3	2.1	21	147
4	3.8	25	157
5	6	29	203
6	8.6	33	231

When the forming parts were observed, forming was found to have been done at 4, 5, and 6 kV excluding 3 kV at which little forming was done as shown in Fig. 6 and as the charging voltage was raised, deformation also increased. In particular, the grids printed on the surface of the work piece were damaged in the case of circle shapes. Such deformation and damage were due to the collision between the work piece and die caused by electromagnetic force. The surface damage occurred at 4kV and 5kV of charging voltage as shown in Fig. 6(a) and 6(b). On the other hand, two surface damages were found in case of 6 kV, and internal damage was more serious than external damage as shown Fig. 6(c).

(a) 4kV (b) 5kV (c) 6kV

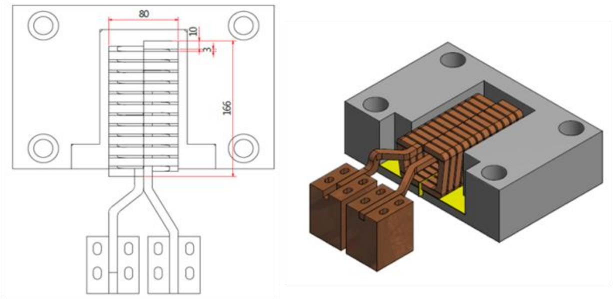
Fig. 6 Contour on work piece using the bar-type forming coil

During magnetic pulse forming, plastic deformation is started due to collide between the forming material and die caused by electromagnetic force. Since the distribution of electromagnetic force is un-uniform depending on the shape of a coil, central part of work piece collides with a die first, and then rebounds. The current density is generally low at the center of a forming coil due to the skin effect which the electricity flows concentrating surface of a forming coil. Especially, skin effect is significant when the frequency is raised and it leads to generate the non-uniform of distribution of electromagnetic force on forming coil and un-uniform dynamic behavior of work piece. According to a previously research by D.A. Oliverira et. al., the air in the die causes the rebound on work piece during forming process. Since magnetic pulse forming is completed within tens of us, the work piece collides with a die at a speed of about 50~200m/s. accordingly, the air in the die does not have sufficient time to leave the die. Consequently, such the air in die causes rebound on work piece during process.

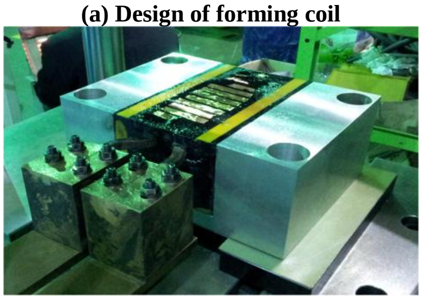
C. Helical-type forming coil

When forming was done using a bar-type forming coil, a rebound occurred due to 15us processing speed and non-uniform of distribution of electromagnetic force. Therefore, a helical-type forming coil was designed to generate uniform electromagnetic force with increased discharge time as shown in Fig. 7.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015



(a) Design of forming coil



(b) Manufacturing the forming coil

Fig. 7 helical-type forming coil

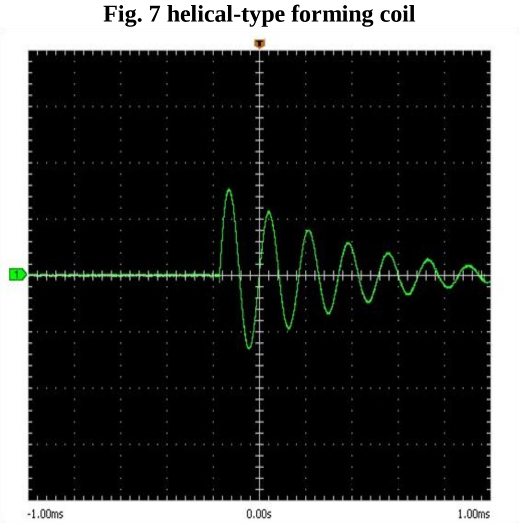
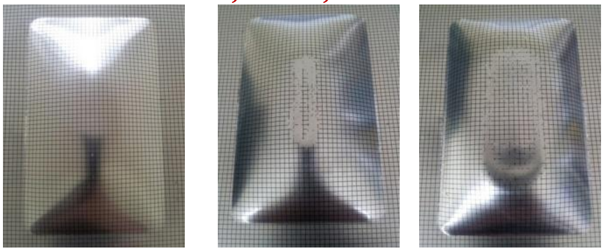


Fig. 8 Discharge waveform (Y: 10v/div, X: 200us/div)

Table 4. Measured peak voltage and current

Charged voltage(kV)	Charged Energy(kJ)	Measured peak voltage (V)	Measured peak current(kA)
3	2.1	6	42
4	3.8	10	70
5	6	14	98
6	8.6	16	112

As shown in Table 4, peak discharge current was about half of that of the bar-type forming coil due to increased coil resistance and inductance. Since the electromagnetic force is determined by the peak current, the charging voltage should be increased to get the same forming depth as the bar-type forming coil. When the forming part was observed, forming was found to have been done as shown in Fig. 9, and deformation increased as the charging voltage was raised. When the forming part was compared with that of the bar-type forming coil, relatively uniform forming part was observed, and rebound was not observed.



(a) 4kV (b) 5kV (c) 6kV

Fig. 9 Contour on work piece using the helical-type forming coil

This result shows that a helical-type forming coil is more effective than a bar-type forming coil in magnetic pulse forming. As the number of experiments was increased, however, deformation was increased in the inside of the forming coil. Such deformation of the coil was caused by the electromagnetic force generated in the coil as shown in Fig. 10.

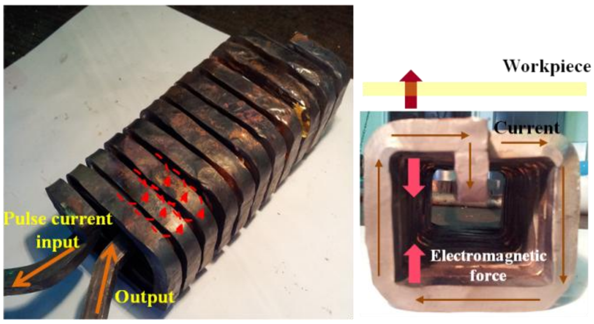


Fig. 10 Electromagnetic force in forming coil

As described above, a helical-type forming coil requires high charging voltage due to the low peak current. When the charging voltage is increased, the electromagnetic force generated in the inside is also increased and the epoxy insulator layer is consequently damaged by deformation of forming coil as shown Fig. 11. This results show the helical-type forming coil generates the uniform electromagnetic force, but method for preventing the deformation of the forming coil are required.

Fig. 11 Deformation of helical-type forming coil

III. MAGNETIC PULSE FORMING WITH ALUMINUM PUNCH

The magnetic pulse forming using punch was developed to establish a magnetic pulse forming process considering the rebound and durability of the coil. A case having 60mm width, 100mm height, 6mm depth, and 2mm bending radius was selected for manufacturing the prototype of small-sized digital electronic product using this technology. The punch was employed aluminum 6061-O plate by considering the electric resistance and conductivity. Fig.12 shows the designed die, SKD11 was employed which have 50HRC by heat treatment.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015

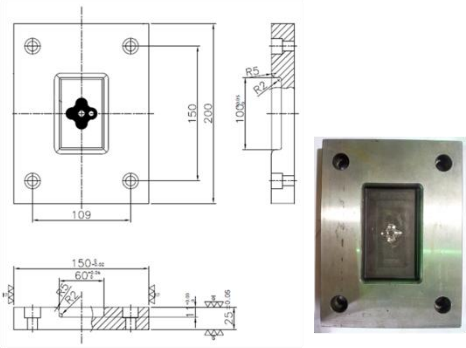


Fig. 12 Die for manufacturing the case

In case of the process wherein forming is done in the required shape when a aluminum punch with work piece is collided with a die by electromagnetic force, the elongation of work piece is instantaneously improved when high-speed kinetic energy is changed to heat energy. The aluminum punch and work piece are located at the upper part of forming coil as shown in Fig. 13 and then electromagnetic force is applied to the aluminum punch.

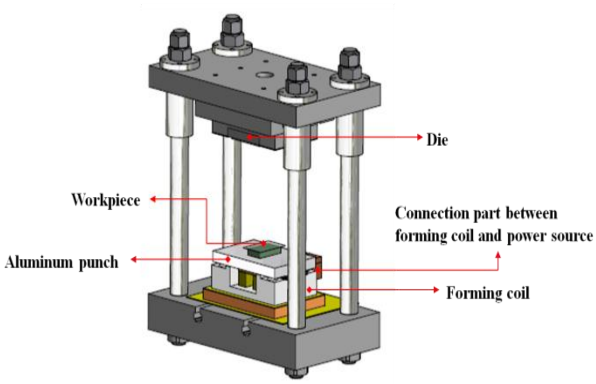


Fig. 13 Magnetic pulse forming with aluminum punch

Therefore, forming coil shape is not limited in this process. The bar-type forming coil which has high durability was employed at 6kV for manufacturing the prototype case. Fig. 14 shows the prototype case using magnetic pulse forming with punch. To analysis the depth on work piece was precisely performed using a 3D scanning as shown Fig. 15. Fig. 16 shows the deformation depth on work piece in magnetic pulse forming with bar-type, helical-type forming coil and punch at 5kV. Although, the curve which used helical-type forming coil was more fluent than curve with bar-type forming coil, successful forming for target shape was not complicated by magnetic pulse forming with two type coil.

Fig. 14 Aluminum case for small-sized digital electronic product

Fig. 15 3D scanning for measuring the deformation depth

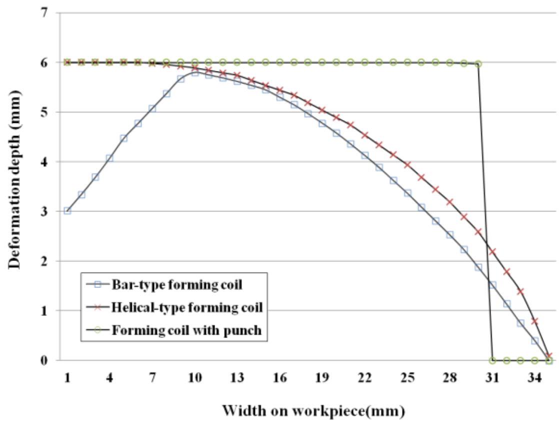


Fig. 16 Deformation depth according to the forming coil shape

According to this result, to use the punch in magnetic pulse forming is most effective process for applying in the site than magnetic pulse forming with two type forming coil. Also, to use developed process is expected to improve productivity in the sites because magnetic pulse forming process is completed within tens of μs.

IV. CONCLUSIONS

This study was focused the development of magnetic pulse forming process for applying the industry site and manufacture the prototype aluminum case for small-sized digital electronic product using developed forming process. The following conclusions were reached:

(1) After the collision between work piece and die, surface damage from the rebound by non-uniform distribution of electromagnetic force and high velocity was observed on work piece with bar-type forming coil. Alto, the number of rebound was increased as electromagnetic force which is applied on work piece increases.

(2) Helical-type forming coil is more effective than bar-type forming coil in EMF process because distribution of electromagnetic force of helical-type forming coil is uniform. So, helical-type forming coil is more effective than bar-type forming coil in magnetic pulse forming. However, the inner electromagnetic force of forming coil caused the serious problem for durability.

(3) The magnetic pulse forming process using punch was developed for considering the industry site. Developed process includes magnetic pulse power source, forming coil, die and aluminum punch for preventing the rebound. The prototype aluminum case for small-sized digital electronic product successful developed using magnetic pulse forming process with punch.

REFERENCES

[1] S. Toros, F. Ozturk., and I. Kacar, “Review of warm forming of aluminum–.magnesium alloys,” journal of materials processing technology, 207, pp. 1-12, 2008.

[2] Wang H., Luo Y., Friendman P., Chen M., and Gao L., “Warm forming behavior of high strength aluminum alloy AA7075,” Trans. Nonferrous Met. Soc. China, Vol. 22, pp. 1-7, 2012.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 4, Issue 2, March 2015
[3] Bolt, P.J., “Feasibility of warm drawing of aluminum products,” J. Mater. Process. Technol., Vol. 115, pp. 118-121, 2001.

[4] Daehn, G. S.m, Vohnout V.J., and DuBois, L., “Improved formability with electromagnetic forming: fundamentals and a practical example. In: Sheet Metal Forming Technology,” The Minerals Metals & Materials Society, pp.105–116, 1999.

[5] Balanethiram, V.S. and Daehn G. S., “Hyper plasticity-increased forming limits at high work piece velocities,” Scr. Metall., Vol. 31, pp.515–520. 1994.

[6] Takatsu N., Kato M., Sato K. and Tobe T, “High speed forming of metal sheets by electromagnetic forces. International J. Japanese Society for Mechanical Engineering,” Vol. 60, pp.142-150, 1988.

[7] G.K. Fenton, “Development of numerical tools to model plasticity in aluminum due to electromagnetic forces,” Master’s Thesis, Department of Materials Science and Engineering, OSU, pp. 28-69, 1996.

[8] G.K. Fenton and Daehn G. S., “Modeling of electromagnetically formed sheet metal,”J. Mater. Process. Technol., Vol. 5. pp. 6-16, 1998.

[9] Oliveira DA, Worswick Mj, Finn M and Newman D, “Electromagnetic forming of aluminum alloy sheet: free-form and cavity fill experiments and model,” J. Materials Processing Technology, Vol. 170, pp. 350-362, 2005.

[10] B. Bendjima, “Finite element modeling of electromagnetic phenomena related to electromagnetic forming,” Doctoral Thesis, Univ. Nantes, pp. 34-61, 1997.

[11] J. Imbert, S. Winkler, M. J. Worswick, D.A. Oliveira and S. Golovashchenko, “The effect of tool/sheet interaction on damage evolution in electromagnetic forming of aluminum alloy sheet,” ASME Int. J. Eng. Mater. Technol., pp. 145-153, 2005.

[12] L. Qiu, X. Han, Q. Hiong, Z. Zhou and L. Li, “Effect of work piece motion on forming velocity in electromagnetic forming,” 5th International conference on high speed forming, pp. 103-112, 2012.

[13] M. Kamal, J. Shang, V. Cheng, S. Hatkevich and Daehn G. S, “Agile manufacturing of a micro-embossed case by a two-step electromagnetic forming process,” J. Materials Processing Technology, Vol. 190, pp. 41-50, 2007.

[14] J. Y. Shim, I. S. Kim, K. J. Lee, and B. Y. Kang, “Experimental and Numerical Analysis on Aluminum/Steel Pipe Using Magnetic Pulse Welding,” Met. Mater. Int, Vol. 17 No.6 , pp. 957-961, 2011.

[15] Stiemer M, UngerJ., Svendsen B., and Blum H., “Algorithmic formulation and numerical implementation of coupled electromagnetic-inelastic continuum models for electromagnetic metal forming,” J. Numerical Methods in Engineering, Vol. 68, pp.1301-1329, 2006.

[16] J.P.M. Correia, M. A. Siddiqui, S. Ahzi, S. Belouettar and R. Davies, “A simple model to simulate electromagnetic sheet free bulging process,” J. Mechanical Sciences, Vol. 50, pp.1466-1475, 2008.

[17] J.Y. Shim, I.S. Kim, M.J. Kang, I.J. Kim, K.J. Lee and B.Y. Kang, “A Study on Joining Al/Steel Pipe Using a Magnetic Pulse Welding,” Materials Transactions, Vol. 52 No.5, pp. 999-1002, 2011.