Experimental Investigation and Analysis on Electromagnetic Compression Forming Processed Aluminum Alloy Tubes

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Abstract

The electromagnetic forming process is high-velocity manufacturing techniques that use electromagnetic forces to shape tube and sheet metal parts. Aluminum alloys are widely used in engineering structures and components where light- weight and corrosion resistance are required. Electromagnetic forming process are successfully employed for the materials that are difficult to form by conventional methods because of spring back, as this process achieves large amount of plastic deformation without spring back. In addition, electromagnetic forming improves mechanical properties of the materials, especially, its hardness, and also increases the rate of production. In this paper, the experimental investigation and analysis on electromagnetic compression forming of aluminum alloy AA6101 tubes is presented. Aluminum alloy tubes of outer diameter 40 mm and wall thickness of 2 mm with a nominal tensile strength of 214 MPa were electromagnetically compressed using a 4 turn helical actuator that discharges energies up to 20 kJ. It is found that a maximum of 15.85% reduction in outer diameter could be achieved during electromagnetic forming at 18 kJ with an approximate discharge current of 160 kA. The post- forming hardness, micro structure and deformed grain size were also studied. The experimental results were correlated with mathematical analysis using MATLAB and also with simulation using ANSYS. The comparison of analytical results with experiment and simulation showed good.

Keywords

Forming, Electromagnetic forming, Deformation, Analysis

1 Introduction

High-velocity electromagnetic forming (EMF) can be a flexible and cost-effective alternative to the conventional metal stamping and forming processes. The circuit of the EMF consists of an EMF machine, part, transmission lines and buses, field shaper and primary coil. The coil is the main tool, whose structural and electrical parameters play an important role in the space distribution of magnetic field, and the peak value and width of the magnetic pressure pulse acting on the part [1-2].In EMF a large capacitor bank is connected in series with a forming coil. Discharging the capacitor bank through the coil results in a large transient current, which in turn induces electric currents in the nearby metallic workpiece. The resulting Lorentz forces cause workpiece motion which caused result in plastic deformation. The input electric energy can be precisely controlled, making the process repeatable, and the non-contact loading allows the use of single side tooling [3].

Metals of high electrical conductivity and of low mechanical strength can be formed by means of pulsed magnetic fields being produced by the sudden discharge from capacitor bank. This technique is especially suitable for the compression of tubes by means of compression coils, i.e. by cylindrical coils surrounding the tubular work piece [4]. Aluminum (Al) and magnesium (Mg) are engineering materials that have high electrical conductivity, low melting point, high vapor pressure, high affinity for oxygen and low-yield strength. Application of heat often leads to serious defects, and hence they are appropriate work materials for electromagnetic forming (EMF) which can be conducted at room temperature [5]. Aluminum, being a light weight material, has wide applications in automobile and aerospace industries. However, formability and weldability still remain major issues for aluminum. Nevertheless, while forming aluminum alloys using high-energy rate forming methods, the formability of aluminum can be significantly increased [6].

In this work, the study on effect of energy level on the magnetic field in electromagnetic tube compression forming is presented. The diameter of aluminum alloy 6101 tubes are formed using standard electromagnetic compression forming equipment manufactured by $PST_{Products}$, GmbH,Alzenau Germany. The changes in tube outer diameter,post-forming hardness and microstructure were measured using standard equipments. A sequential coupled FEA simulation was attempted to simulate the electromagnetic tube compression using the FEA Multi-physics software ANSYS 13.0. The effects of tube deformation were taken into account during the coupling between the magnetic and the structural analysis. The results on changes in tubes outer diameter with time are presented. The simulation showed good agreement with experimental and mathematical analysis carried out using MATLAB 2010.

2 Overview of the compression experiments

The Aluminum alloy AA6101 tubes of outer diameter 40 mm and wall thickness of 2 mm were selected to study their response to compression forming using EMF.The properties of the alloy are summarised in Table 1.

The experimental setup consisted of a coil, a split field shaper and a specimen holder, which allows for aligning the tube and insert inside the coil, as shown in Figure 1. The machine had maximum charging capacity of 20 kJ and a discharge circuit frequency of 6.5 kHz. The coil was designed with 4 turns and rectangular cross section with dimensions of 26 mm in width and 10 mm in height. The total capacitance of the capacitor banks was 400 μF. The resistivities of the tube and coil materials were measured as 3.2×10^{-8} Ωm and 1.7×10^{-8} Ωm respectively. The compression was performed on sudden release of energy stored in four capacitors with a total inductance of 450 nH.

Chemical composition (wt %)	Fe:0.209%,Si:0.384%,Mg:0.387%,Mn:0.020% Cu:0.002%,Ti:0.002,Pb:0.023%,Al:98.961%
Yield stress (MPa)	188
Tensile strength (MPa)	214

Table 1: *Properties of AA 6101*

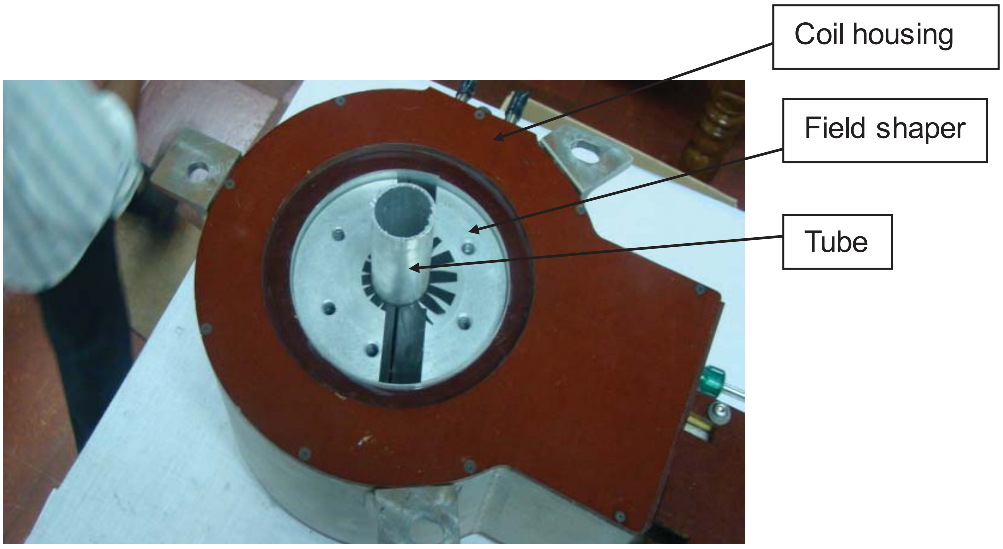


Figure 1: *The experimental set-up of coil, field shaper and tube*

2.1 Effect of energy levels in tube compression

The work pieces were positioned inside the field shaper in the overlap configuration. The energy levels lesser than 6 kJ were not considered, as it had no appreciable formability. The maximum energy was limited to 18 kJ, as further increase in energy level would have caused failure. Hence experiments were conducted at different energy levels 6 kJ, 8 kJ, 10 kJ, 12 kJ, 14 kJ and 18kJ. The electromagnetically compressed aluminum alloy tube specimen at various energy levels is shown in Figure 2. The final outer diameters of the non–round deformed tubes were estimated by taking the average of the outer diameter measured using vernier calipers. The final reduced outside diameter for various energy levels are tabulated in the comparison table, Table 2.

2.2 Microstructural Observations

The microstructures of the parent material and the compressed tube material formed by electromagnetic compression were observed using optical microscope. The image of the microstructure of parent material and electromagnetic compression formed at an energy level of 18 kJ are displayed in Figure 3 & 4 respectively. The parent material of the tube does not show any grain flow along the longitudinal section whereas all the electromagnetically formed tube showed banding of grains along the direction of forming.

The grain size of the specimen before forming is lower as compared to the grain size of the specimen after EMF process. This in turn had caused an increase in the mechanical properties specifically the hardness in the electromagnetically processed alloy as shown in comparison table, Table 3.

Figure 2: *Electromagnetically deformed tube specimen at various energy levels*

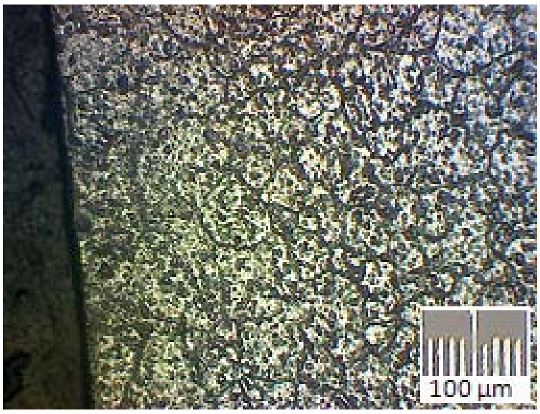


Figure 3*: Longitudinal section of parent alloy*

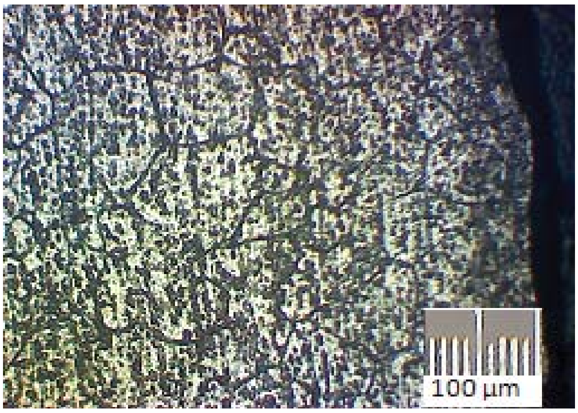


***Figure 4**: Longitudinal section of EMF specimen at 18 kJ*

2.3 Hardness Measurements

In order to investigate the hardness of the tube, Vickers hardness measurements were performed using a Wilson Wolpert Micro Hardness tester with a test load of 0.5 kg and an indentation time of 12 sec. The measured hardness image of Scanning Electron Microscope of the electromagnetic compression formed aluminum alloy specimen is shown in Figure 5. The hardness of the aluminum alloy materials were measured well outside the deformed zone. The electromagnetically formed zone shows an increase in hardness relative to the base materials. This can be attributed due to the severe plastic deformation or new fine-grained microstructure produced by electromagnetically formed zone. The measured post formed hardness of the tube for various energy levels are shown in the Table 3.

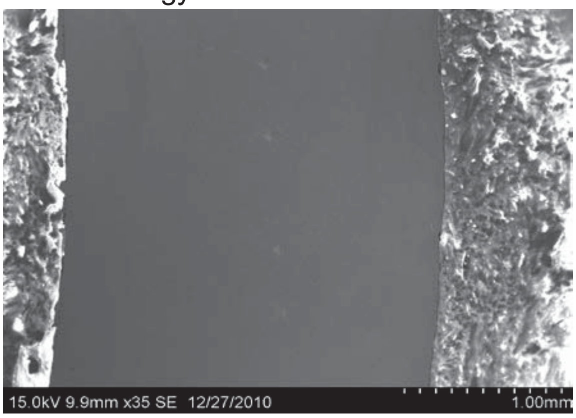
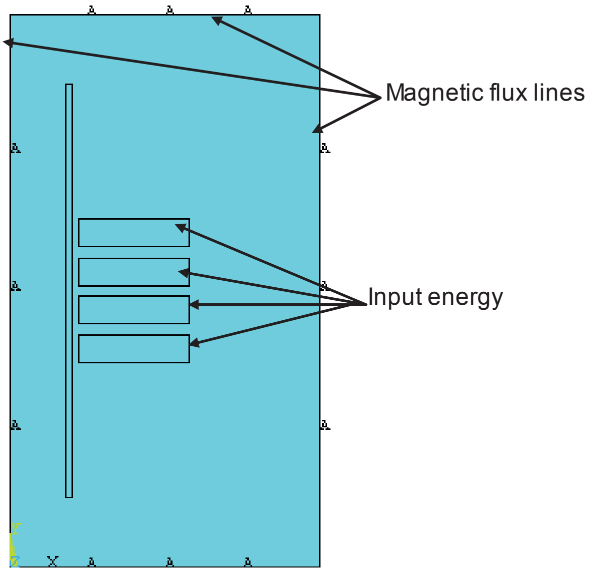


***Figure 5:** SEM micrograph of aluminum alloy specimen for measuring Vickers hardness*

3. Finite Element Analysis of the Compression Process

The simulation of the electromagnetic compression process was carried out using ANSYS 13.0 by assuming: (a) the solenoid coil to be concentric with the tube and (b) without any field shaper between the coil and tube. An Axisymmetric 2D model was considered for both magnetic and structural analysis. The Plane 13-2D, 4 Node solid element was considered, as it can support both magnetic and structural analysis. The element had degrees of freedom U_X,U_Y,and current density (AZ) for magnetic analysis and U_X and U_Y for structural analysis.



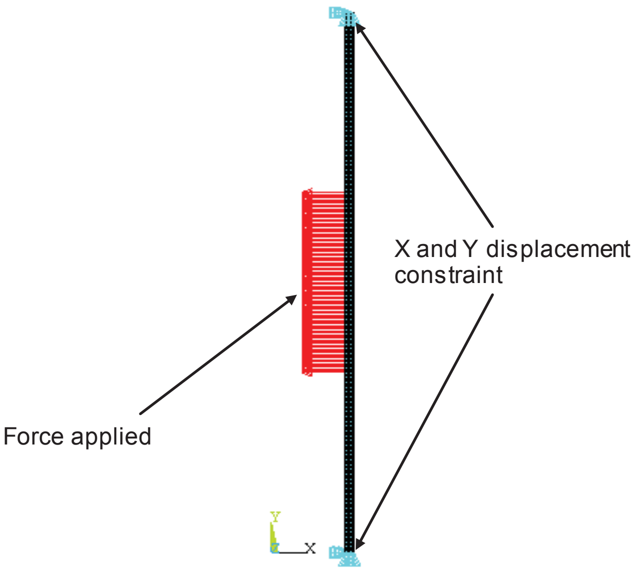


Figure 6: *Boundary Conditions for Magnetic Analysis*

Figure 7: *Boundary Conditions for Structural Analysis*

The aluminum alloy work piece and the current carrying coil is modeled in 2D considering rectangular cross section for both the coil and the work piece. All the edges of the air medium is constrained for flux lines and the input energy is applied in the coil as shown in Figure 6. The size of the air medium is 100x200 mm.The various energy levels were given as input to carry out the magnetic analysis.The boundary conditions for structural analysis is illustrated in Figure 7. The resulting magnetic force simulated from the magnetic analysis is sequentially coupled to carry out the structural analysis. The Figure 8 shows the deformed tube at an energy level of 18 kJ after the analysis.There was reduction in outer diameter of 6.309 mm at 9 µs in the radial direction. The reduction in final outside diameter for various energy levels are tabulated in Table 2.

Figure 8: *The sectional view of the deformed tube for an energy level of 18 kJ at 9 µs*

4 Mathematical analysis of the Compression Process

The MATLAB 2010 software was used to analyse the electromagnetic process. A simple mathematical expression used to calculate the decrease in the diameter (δ) of the tube is given below [7].

$$\delta = \left(\frac{DP}{2E}\right) \times \left(\frac{D^2 + d^2}{D^2 - d^2} - \gamma\right) \qquad (1)$$

Where,
D is the Outside diameter of the tube,
P is the magnetic Pressure, P=F/A, F-magnetic force and A-surface area.
d is the Inside diameter of the tube,
E is the Young's modulus of the tube material,
γ is the Magnetic permeability of the tube material.

A code in MATLAB was developed based on the below algorithm.

- Initialise the Variables
- Set the Input Variables
- Fix Constants
- Code the equation in MATLAB format and get the output result for the mathematical expression. For dual cases , 'if' command is used
- For thin walled 'if' is pre-set and for thick walled 'else if' is pre-set and is set as a loop.
- Output parameters are obtained in the form of text followed by the value string format

5 Results

The results obtained from the experiment, Finite element and mathematical analysis are shown in Table 2 and Figure 9. The measurement of the hardness were carried out experimentally for different energy levels as shown in Table 3.

Energy Level (kJ)	Final OD by Experiment (mm)	Final OD by MATLAB (mm)	Final OD and time taken by Simulation	
			(mm)	(µs)
6	39.50	39.25	39.50	3
10	38.18	37.93	38.13	5
12	37.50	37.02	37.56	6
14	36.45	35.95	36.54	7
18	33.66	33.30	33.69	9

Table 2: *Comparison of results*

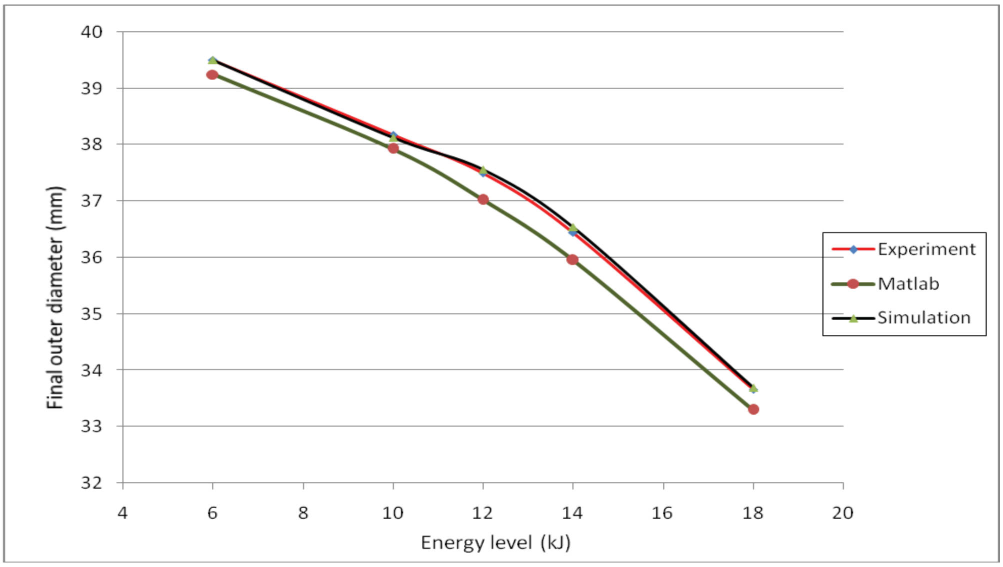


Figure 9*: Tube diameter at different energy levels*

Energy Level (kJ)	Deformation by Experiment (mm)	Vickers Hardness (HV)
6	0.50	74.9
10	1.82	76.3
12	2.50	77.2
14	3.55	78.7
18	6.34	83.7

Table 3: *Vickers hardness at different energy levels*

The microstructure analysis of the compressed tube using optical microscope has showed elongation and new grain formation along the longitudinal direction of the tube. The Vickers hardness measured using micro hardness tester has also showed an increase in hardness of the tube with increase in energy level. It is easy to infer that with increase in energy level, the resulting compression (reduction in outer diameter) is more and the entire process has been carried out in less than a second. As the entire forming has been done in quick timing, no spring back was observed. The simulation carried out using the Finite element and mathematical analysis software showed very good agreement with the experimental result. It is inferred from the experiment that, the use of electromagnetic forming technique is advantageous in compression forming applications as reflected from the results.

6 Conclusions

In this study, electromagnetic compression forming experiments were performed to investigate the deformation behaviour and mechanical properties of aluminium alloy tubes of 40 mm outside diameter and 2 mm wall thickness. It is observed from the experiment that by increasing the forming energy there is increase in reduction in diameter during compression process. It is also observed that as the energy level is increased, the value of the hardness too is increased. The measured values of Vickers hardness show an increase of 10.0 HV at the highest energy level. This has proved that the use of EMF technology would increase the mechanical properties of the alloy. The Plane 13-2D 4 noded element used in the sequential coupled electromagnetic analysis simulated the process very accurately.

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References

[1] *Kleiner, M.; Beerwald, C.; Homberg, W.*: Analysis of process parameters and forming mechanisms within electromagnetic forming process. CIRP Annals−Manufacturing Technology, 2005, 54(1), p.225−228.

[2] *EL-Azab, A.; Garnich, M.; Kapoora, A.:* Modeling of the electromagnetic forming of sheet metals: State-of-the-art and future needs. Journal of Materials Processing Technology, 2003, 142, p.744−754.

[3] *Balanethiram, V.; Daehn, G.:* Enhanced formability of interstitial free iron at high strain rates. Scripta Metallurgica et Materialia, 1992, 27, p.1783–1788.

[4] *Jablonski, J.; Winkler, R.*: Analysis of the electromagnetic forming process. Int. J. Mech. Sci. 1978, (20), p. 315–325.

[5] *Plum, MM*,: Maxwell Laboratories Inc. Electromagnetic forming, metals handbook, 9th ed. 14 ASM Metals Park, OH; 1996.

[6] *Balanethiram, V.: Hyperplasticity*: enhanced formability of sheet metals at high velocity. PhD thesis, Material science and engineering.Columbus, OH, USA: The Ohio State University, 1996.

[7] *Srinath L S*.: Advanced Mechanics of Solids.Tata McGraw-Hill Publishing Company limited, India, 2003.