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

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1.EMF Process – Introduction

What is HERF ?

- High-energy rate forming (HERF) refers to processes that form parts at very high velocities and pressures.

- HERF processes involve a short,sharp,forming usually of microsecond duration.

- The resulting force to force the part into a die cavity that has the desired shape of the finished part.

- HERF will typically improve material properties.

- HERF family:
    - Electromagnetic forming
    - Explosive forming
    - Electro hydraulic forming

History of EMF

- 1897-Tesla had Explored principles of the phenomena.
- 1924-One of the earliest developments in producing a short-duration, high-intensity magnetic field was reported by Kapitsa.
- 1950-strong pulsed magnetic fields were used for very fast forming operations working on materials with high electrical conductivity.
- 1959-Electromagnetic forming (EMF) processes principle has been patented by Harvey and Brower.
- 1960-Langlois reported the use of expandable wire coils for magnetically swaging small tubular parts.
- 1962-The first commercial magnetic forming machine was marketed

What is EMF?

- EMF is a high speed forming process using a pulsed magnetic field to form workpieces made of metals with high electrical conductivity such as copper or aluminum alloys.
- EMF used for compression or Expansion of tubes as well as for sheet metal forming.

Process principles

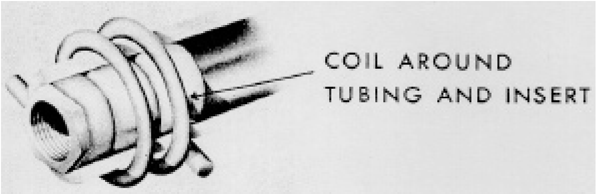


Figure1 : A spiral coil used for tube compression

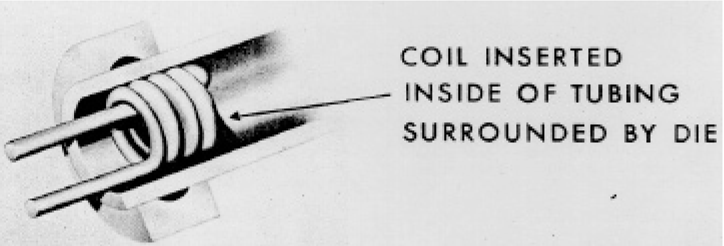


Figure 2 : A spiral coil used for tube expansion

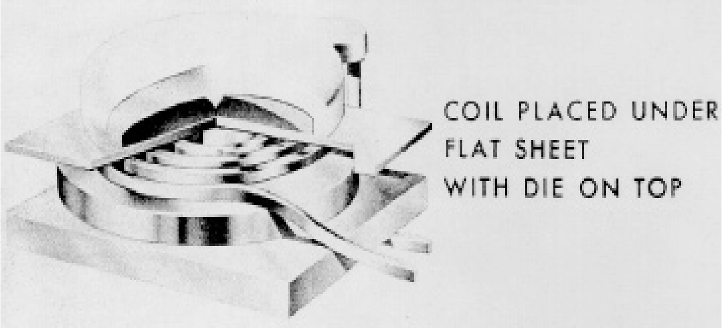
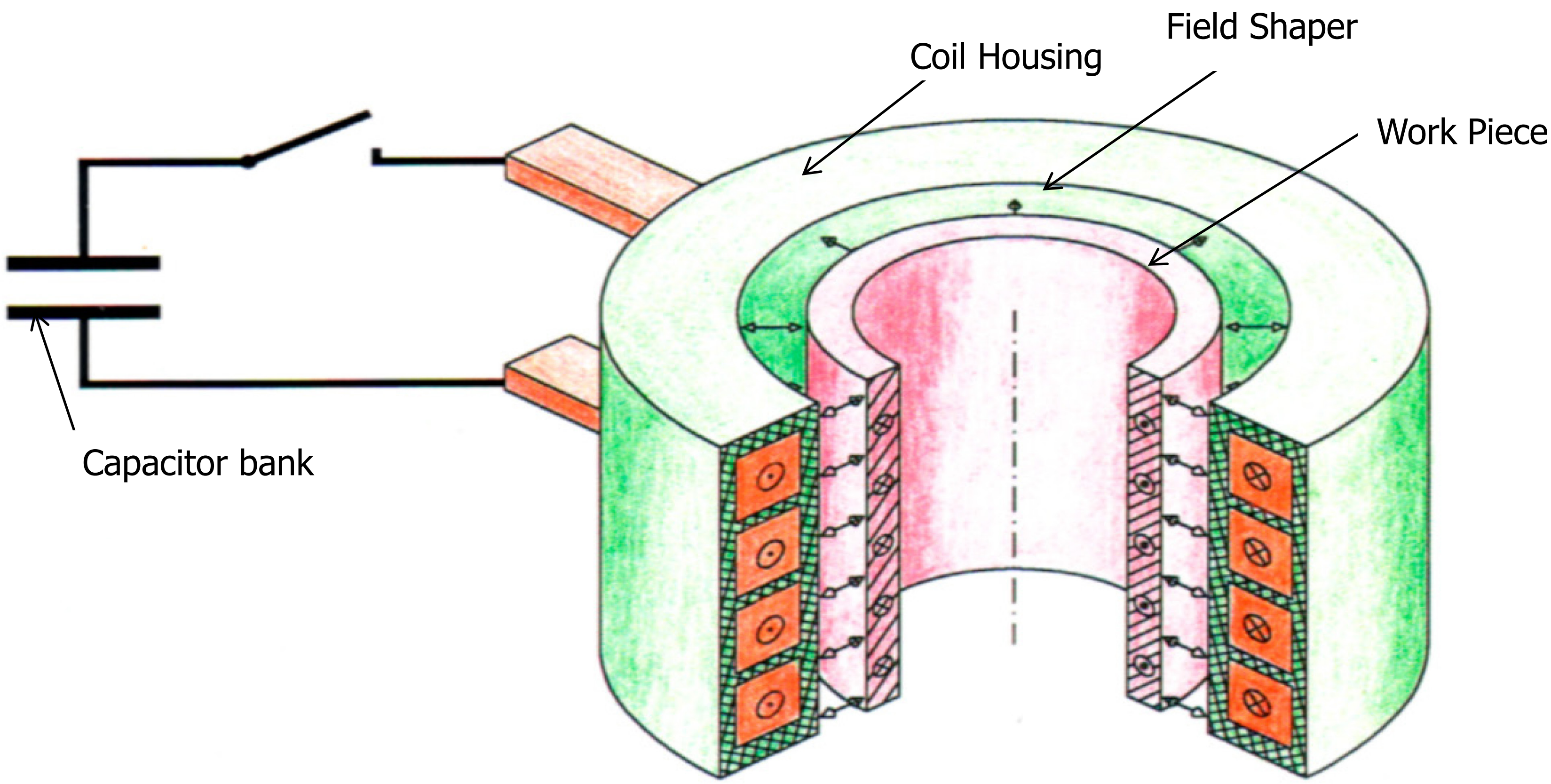


Figure 3 : A flat coil used to form sheet metal

Schematic illustration of Electromagnetic Forming

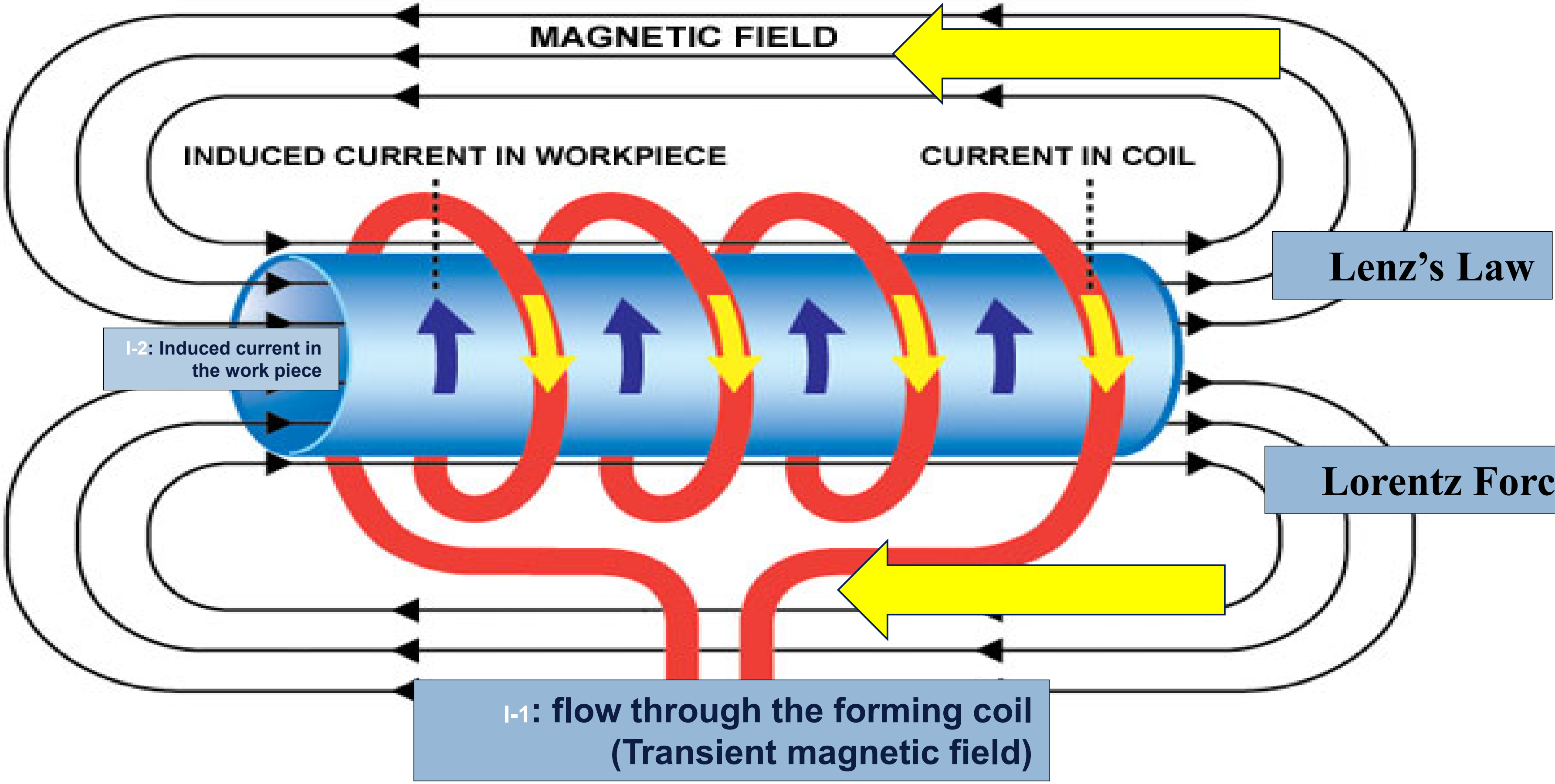


Working principle

- When the switch is closed, electrical energy stored in the *capacitor bank* (left) is discharged through the *forming coil* (orange) producing a rapidly changing magnetic field which induces a current to flow in the metallic *workpiece* (pink).

- The current flowing the work piece produces a corresponding opposite magnetic field which rapidly repels the work piece from the forming coil, reshaping the work piece - in this case, compressing the diameter of the cylindrical tube. The reciprocal forces acting against the forming coil are resisted by the '*supportive coil casing* (green).

Physics of the EMF operation



Approximate Deformation Velocities

Process	Velocity m/sec (f/sec)
Hydraulic press	0.03 (0.10)
Brake press	0.03 (0.10)
Mechanical press	0.03-0.73 (0.1-2.4)
Drop hammer	0.24-4.2 (0.8-14)
Gas-actuated ram	2.4-82 (8-270)
Explosive forming	9-228 (30-750)
Electromagnetic forming	**27-228 (90-750)**
Electro hydraulic forming	27-228 (90-750)

Details	Explosive forming	Electro hydraulic forming	**Electromagnetic forming**
Size limits	1.5 to 6 m dia	1.2 m dia	0.3 m dia
Shape complexity	Simple	Complex	Complex
Capital cost	Low	Moderate	Moderate to high
Tooling cost	Low	Low	Moderate to high
Production rate	**0.5-4** pts/hr	**To 50** pts/hr	**To 1000** pts/hr
Lead time	Short	Moderate	Moderate to long
Facility	Remote	In-plant	In-plant
Operating cost	High	Low	Medium

Applications of EMF

- The automotive industry to form swage copper rings around rubber seals in automotive ball joint assemblies.

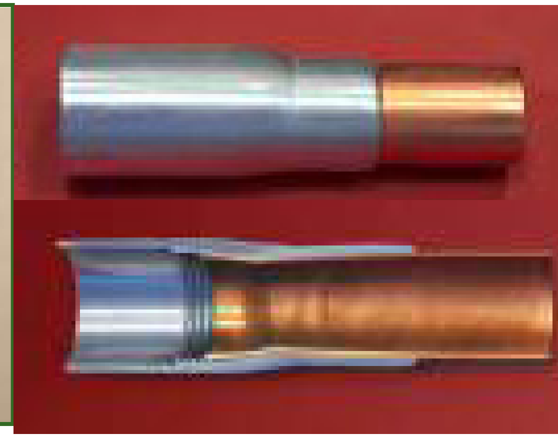
- The forming and installing retaining bands onto oil filters that are used for aircraft and off-road vehicles.

- The repair of dents in aircraft and spacecraft using electromagnetic dent puller.

- Industries like Automotive, Nuclear, Aerospace, HVAC, Defence, Home appliances and Electrical/power industry.

Automotive Applications

Driveshaft:
Al-St, St-St



Tubes of
Dissimilar Metals

Stainless Steel
Exhaust

Al Body
Construction
Elements

Aluminum
Interfaces for Hydro
Formed Steel

Body Parts

Automotive Applications

Automotive Fuel Filters

Electric Fuel Pump Assembly

Automotive Climate Control Elements

Temperature Control and Thermostat Assemblies

Shock Absorber Assembly & Shock Absorber Components

Aerospace Applications

- Torque Tube Assembly
- Tubular space frames
- Duct Work Forming
- Assembly of Diverse Tube Sections to Bulkheads
- Push Pull Rod Assembly
- Oil Filter Assembly
- Projectile Banding
- Diverse Rocket and Missile Components Assemblies
- Flare Assembly
- EMI Proof Electrical connector

Example

Advantages of EMF

The EM forming process has several advantages over conventional forming processes. The advantages include

I. Significant improvement in formability.
II. Wrinkling can be reduced and even eliminated.
III. Very close tolerances are possible as springback can be made minimal or even completely eliminated.
IV. Single sided dies are sufficient which can reduce tooling costs
V. Forming and assembly operations can be combined into a single operation.
VI. Since there is no mechanical contact with the workpiece (as compared to the use of a punch in conventional processes), surface finish can be given to the workpiece before forming.
VII. High production rates are possible.
VIII. It is an environmentally clean process as no lubricants are necessary.
IX. Applicable to high-volume production

2.Objectives

Objectives

- To investigate the role of forming aluminum alloy material and determination of Mechanical property, strain rate and deformations.
- Development of Finite Element simulation model for Electromagnetic Forming technology.
- To analyse the Electromagnetic compression process using MATLAB.
- Comparing the Experimental results with Simulation and Mathematical Analysis.

3. Overview of the Compression Experiments

3.Experimental approach

3.1. Capacitor banks

i. Machine Capacity	- 20 kJ
ii.Charging Voltage	- 10 kV
iii. Circuit frequency	- 6.5 kHz
iv.Circuit capacitance	- 400 μF
v. No of banks	- 4

3.Experimental approach

3.2. Solenoid coil

i. No of turns	- 4
ii. Material	- copper
iii. Max. electromagnetic pressure	- 110 MPa
iv. Coil inner Diameter	- 154 mm
v. working height	- 135 mm

- A Photographs of the 4-turn solenoid coil built by PST Products, GmbH is shown in Figure 1

Fig.1 Photographs of the 4-turn solenoid coil built by PST Products, GmbH.

3.Experimental approach

3.3. Field shaper

- A mylar sheet was used between the coil and aluminum tube to be compressed as extra level of protection of arcing.
- A field shaper made of aluminum was used. Tape with enough dielectric strength was applied around and inside the field shaper to prevent arcing. A field shaper in the experimental set up is shown in figure 2.

Fig.2 Field shaper in the experimental set up

3.Experimental approach

3.4. Materials

i. Material	- AA 6101
ii. Outer diameter	- 40 mm
iii. Inner diameter	- 36 mm
iv. Thickness of the tube	- 2 mm
v. Sample length	- 150 mm
vi. Tensile strength	- 214 Mpa

3.Experimental approach

3.4. Materials

- The chemical composition of an aluminum (6101 type) alloy with 0.387% Mg, 0.384% Si, 0.209% Fe, and 98.961% Al.
- Experiments were conducted at different energy levels. Deformation is recorded using advanced instrumentation.
- The overall setup for these experiments is shown in Figure 3 & 4.

Fig.3 Front view of the typical experimental configuration.

Fig.4 Experimental configuration showing the bank selection, % Energy level, Operating panel and Diagnostic panel.

3.Experimental approach

- The results of all the physical experiments conducted on 20 kJ capacitor bank for compression of tubes 40 mm diameter and 2 mm thickness at different energy levels are shown in Table 1.
- The final OD for a non –round tube is estimated by taking the average of the OD measured using vernier calipers.
- Similarly when the energy level is increased the value of the hardness also increased this leads to property of the materials will be increased as shown in Table 2.
- The electromagnetically compressed aluminum tubes specimens for various level of energy from 6 kJ to 18 kJ are shown in Fig.5,

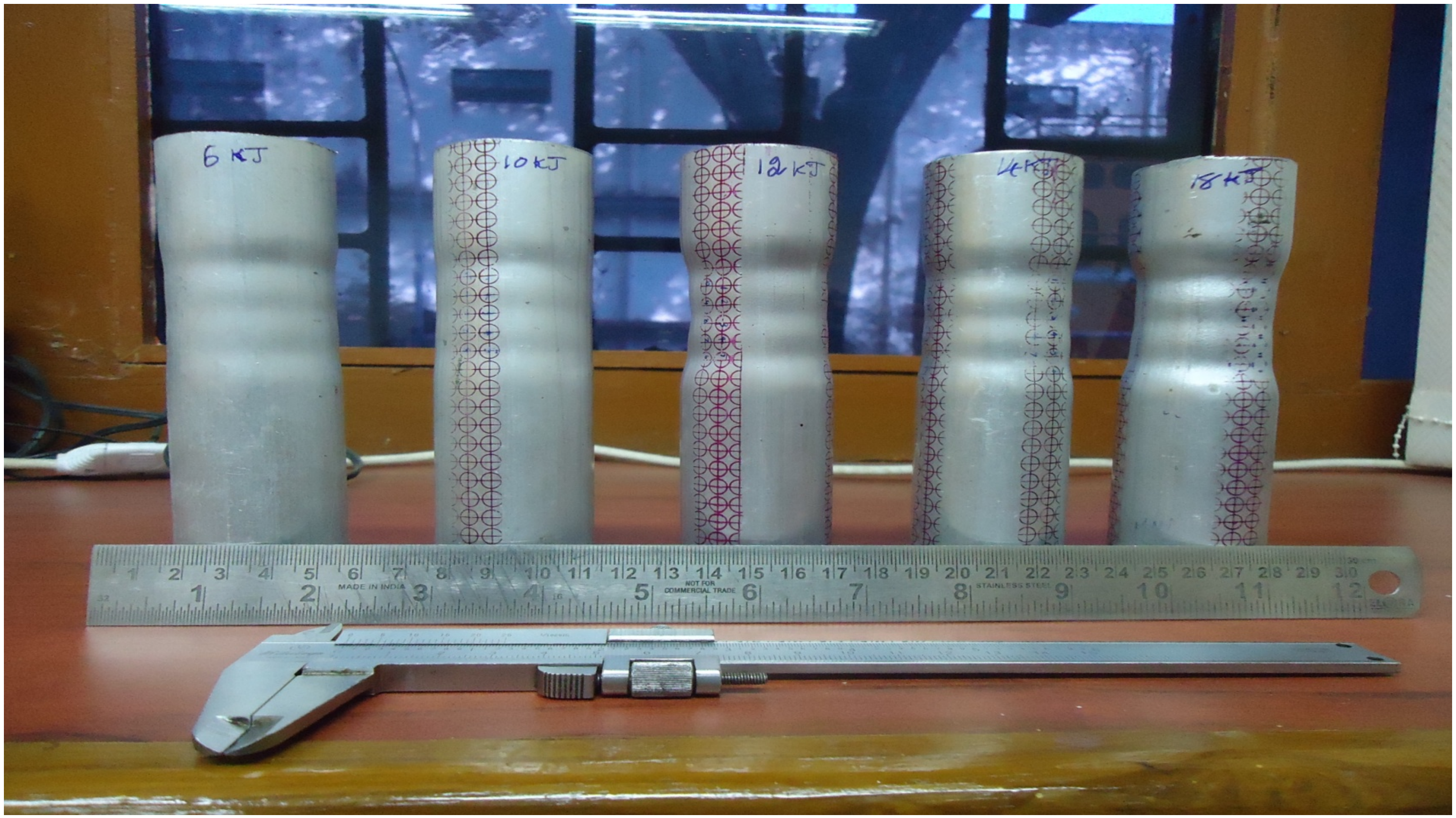


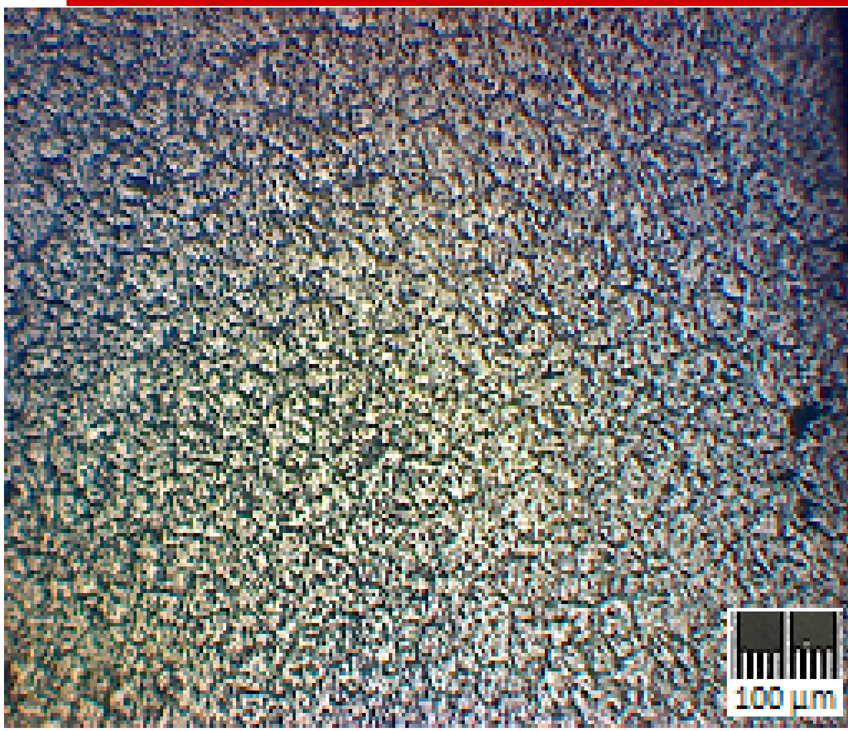
Fig.5 Results of EM-compression tests.

3.Experimental approach

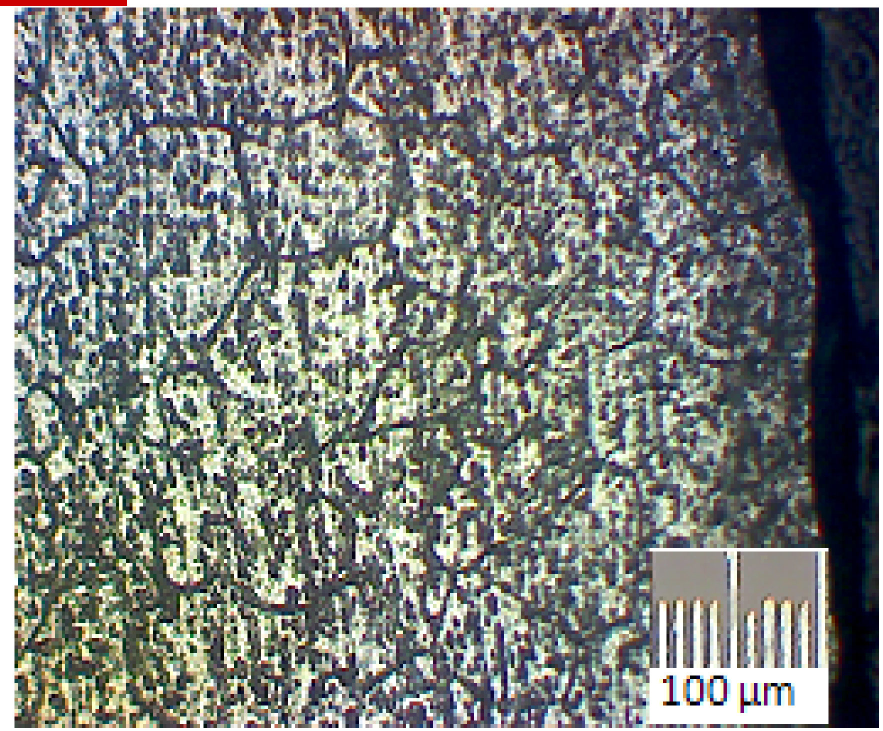
- The microstructure of the parent material and Electromagnetic compression forming tubes are displayed in Figure 6 (a-b).

- In the longitudinal section of the parent material tube does not show grain flow along the direction of forming, whereas the tube after electromagnetic forming shows the banding of the grains along the direction of the forming.

- The grain size of the specimen before forming is seem to be lower compared to the grain size of the specimen after EMF process.



a) Parent alloy for longitudinal section



b) EMF specimen at 18 kJ for longitudinal section

Fig.6 (a-b) Microstructure of the AA parent and EMF tubes

4.Finite Element analysis of the Tube Compression Process

4.FEA approach

- The Finite element analysis is carried out with solenoid coil assumed to be concentric with the tube and placed outside the tube to do the compression process.
- 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.

4.FEA approach

- Material Properties
  - Coil
    - Relative permeability = 1
    - Resistivity = 1.7×10^{-8} (Ωm)
  - Work piece
    - Density=2700(kg/m^3)
    - Young's modulus=71 Gpa
    - Poisson ratio=.34
    - Relative permeability=1
    - Resistivity=3.2×10^{-8} (Ωm)

4.FEA approach

- The 2D model and the current distribution in the massive conductors is illustrated in Fig.7.
- The resulting magnetic force simulated from the magnetic analysis is sequentially coupled to carry out the structural analysis.
- The coupled electromagnetic analysis is carried out for various energy levels 6 kJ, 10 kJ, 12 kJ, 14 kJ and 18 kJ.
- The deformed tube at an energy level of 18 kJ after the analysis as shown in Fig.8
- The reduction in final outside diameter for various energy levels are tabulated in Table 1

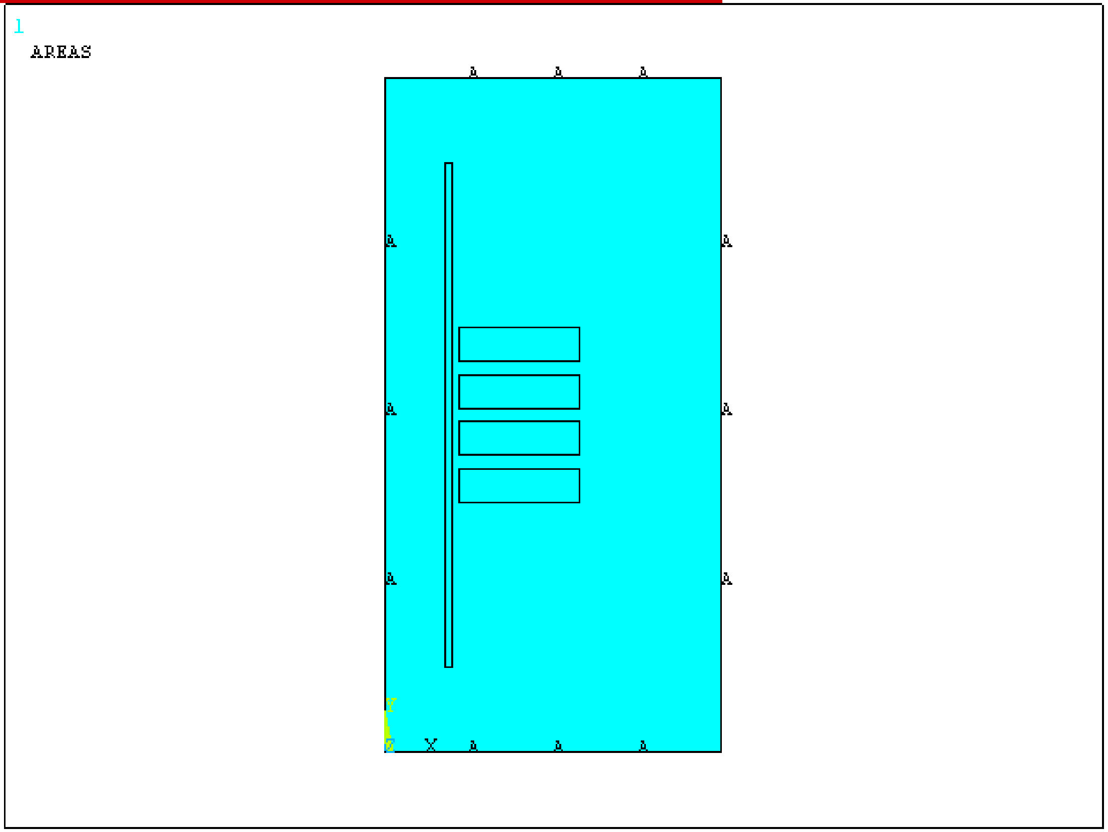


Figure.7 . 2D Model and the current distribution in the coil

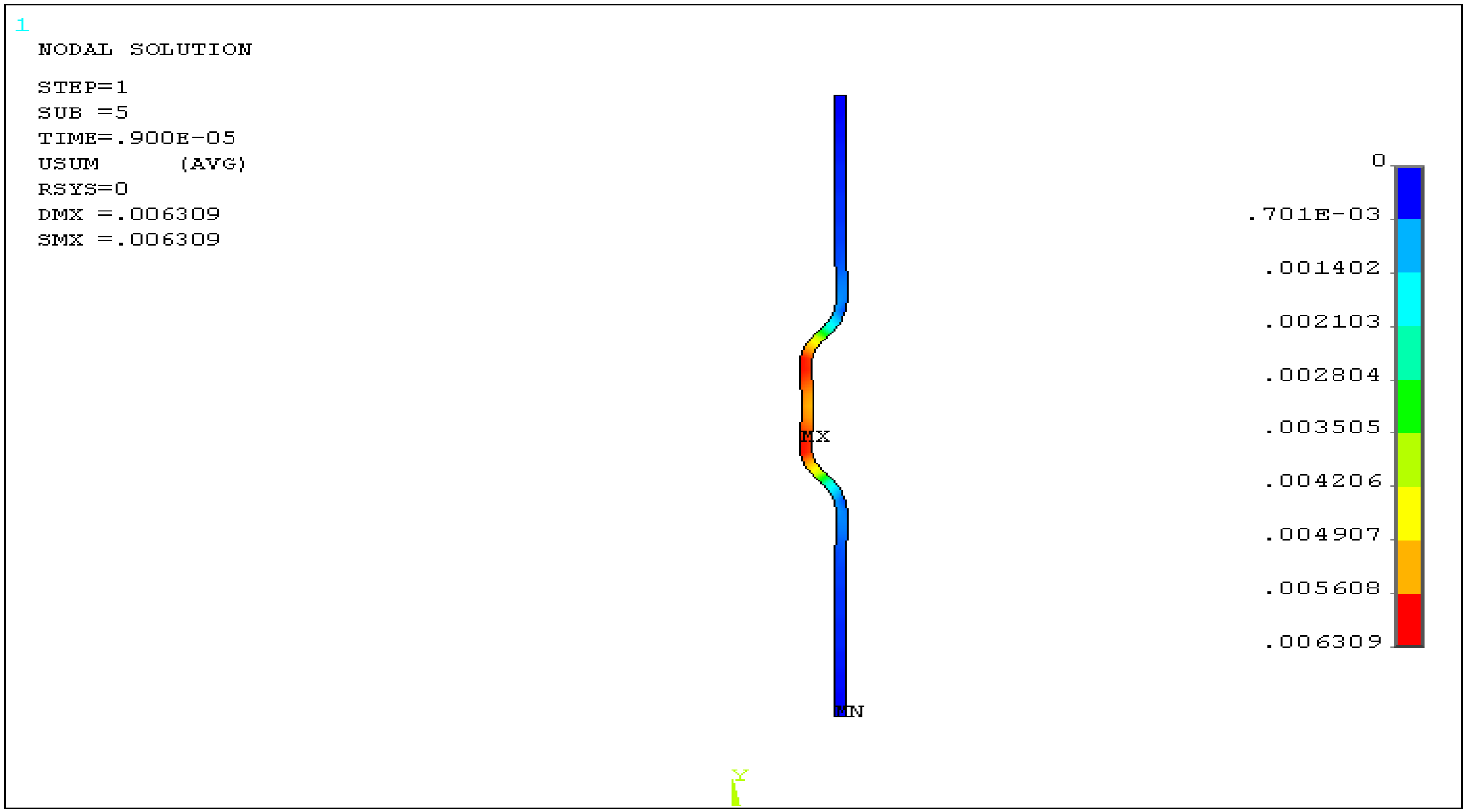


Figure.8 . The sectional view of the deformed tube for an energy level of 18 kJ at 9 μs

5.Mathematical analysis of the Compression Process

5.Analytical approach

- 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].

$$\delta = (DP/2E) X (D^2 + d^2 / D^2 - d^2 - \gamma)$$

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.

5.Analytical approach

- 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

MATLAB Code

```
clear
clc
format long
N=input('enter the number of turns:' );
I=input('enter the current rating: ');
D=input('enter the outside diameter: ');
d=input('enter the inside diameter: ');
L=input('enter the length of the cylinder: ');
t=input('enter the thickness of the cylinder:
');
M=1.256*10^-7;
B=M*N*I/(pi*D);
V=0.3;
E=0.7*10^11;
A=pi*D*L;
F=(B^2*A)/2*M;
P=F/(pi*D*I);
if t>0.1
   D1=((D*P/E)*((D^2)+(d^2))/((D^2)-
(d^2))-V);
   fprintf('Decrease in diameter of the
cylinder %s\n',D1);
elseif t<0.05
   T1=P*D/4*t;
   T2=P*D/2*t;
   D2=(D/E)*(T2-T1);
   fprintf('Decrease in diameter of the
cylinder %s\n',D2);
end
fprintf('Magnetic field = %f\n',B);
fprintf('Pull or Push force of an
electromagnet = %s\n',F);
fprintf('Pressure applied on cylinders =
%s\n',P);
fprintf('Pressure applied on cylinders =
%s\n',P)
```

6.Results

6.Results

- The results obtained from the experiment, Finite element and mathematical analysis are shown in Table 1 and Figure 9.

- The measurement of the hardness were carried out experimentally for different energy levels as shown in Table 2.

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 1: Comparison of results

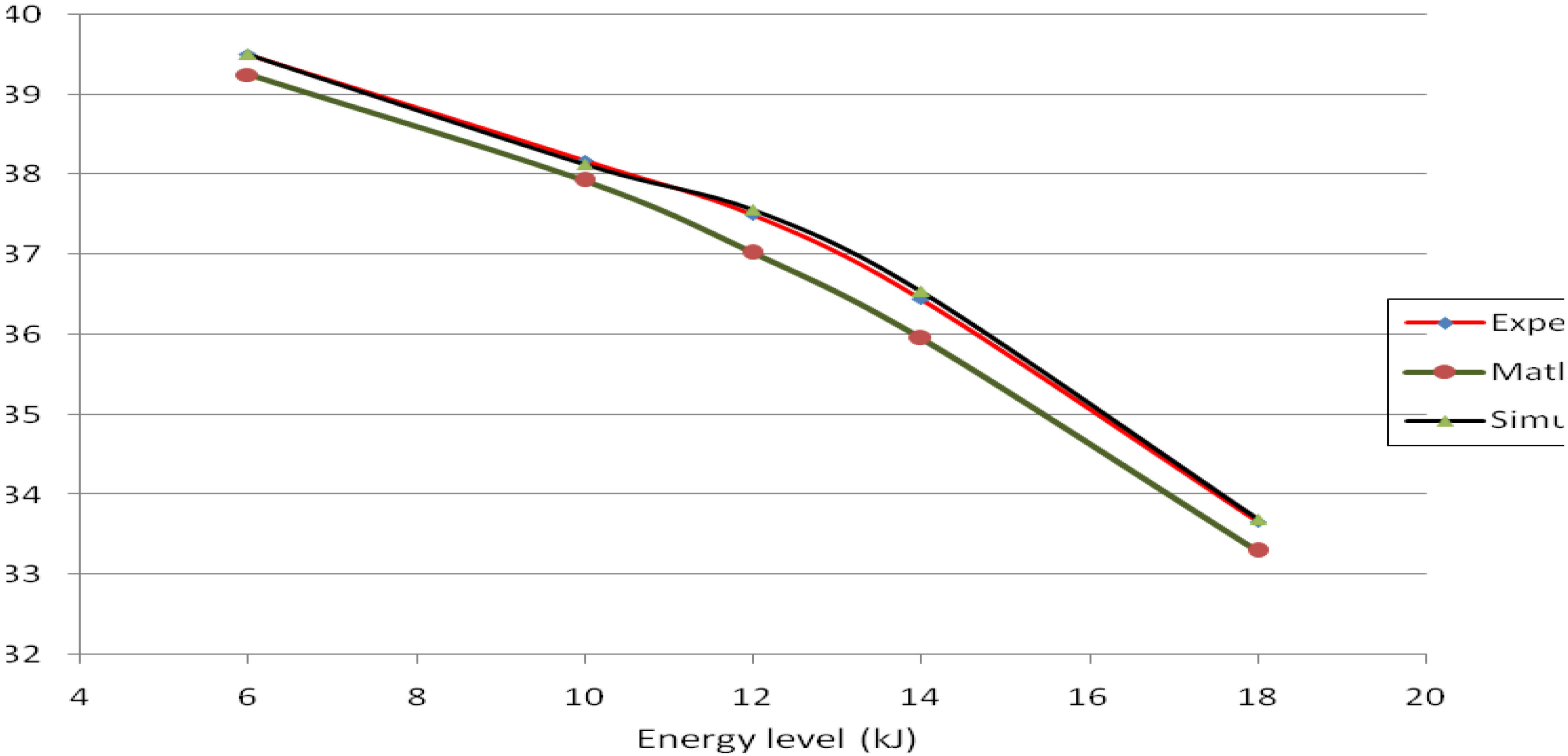


Figure 9: Tube diameter at different energy levels

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 2: Vickers hardness at different energy levels

6.Results

- 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.

- The simulation carried out using the Finite element and mathematical analysis software showed very good agreement with the experimental result.

7.Conclusions

7.Conclusions

- In this work, Electromagnetic compression free forming of Aluminum alloy 6101 tube of diameter 40 mm and thickness 2 mm an experimental, coupled electromagnetic analysis using ANSYS 13.0 and Mathematical analysis using MATLAB are presented.

- It is observed from the experiment that by increasing the forming energy there is increase in reduction in diameter during compression process.

7.Conclusions

- 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.

8.Acknowledgements

8.Acknowledgements

- The authors would like to thank $PST_{Products}$, GmbH, Alzenau, Germany for providing the experimental work support.

9.References

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