B. TECH. PROJECT REPORT

On

Analytical analysis of electromagnetic forming and study of crimping coil

BY

MUDENTI MRUNALINI

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

November 2023

Analytical analysis of electromagnetic forming and study of crimping coil

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

Submitted by:
Mudenti Mrunalini (200003048)

Guided by:
Dr. ASHISH RAJAK (Assistant professor), IIT INDORE

INDIAN INSTITUTE OF TECHNOLOGY INDORE
November 2023

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"**Analytical analysis on electromagnetic forming and study of crimping coil **"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. Ashish Rajak (Assistant professor)**, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Mudenti Mrunalini (200003048)
B.Tech IV Year
Department of Mechanical Engineering
Indian Institute of Technology Indore

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CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. Ashish Rajak

Assistant Professor

Department of Mechanical Engineering

Indian Institute of Technology Indore

PREFACE

This report on "Analytical analysis on electromagnetic forming and study of crimping coil" is prepared under the guidance of Dr. Ashish Rajak.

Through this report, I have researched and analyzed multiple methods to study the crimping coil with the help of my mentor.

I have tried to the best of my abilities and knowledge to explain the content clearly. I have also added 3-D models and figures to make it more illustrative.

Mudenti Mrunalini
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

ACKNOWLEDGEMENTS

I would like to express our gratitude to **Dr. Ashish Rajak** for allowing me to participate in this research. Throughout the process, I appreciate his counsel and collaboration. I owe him a debt of gratitude for sharing his extensive knowledge and experience in the field of Electromagnetic forming and its applications.

My sincere thanks go to **Mr. Ummed Singh** for their help and support. His availability of theoretical knowledge and solutions for many difficult problems that occurred while performing experiments took me smoothly to my results.

It was their help and support, that I became able to complete the design and technical report.

Mudenti Mrunalini
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

ABSTRACT

Faraday's law of electromagnetic induction is the base for the EMF process. This process involves passing the capacitor bank's discharge current through the crimping coil, which generates an internal magnetic field that further induces eddy currents in the conductive workpiece. This results in the opposite direction of Lorentz's forces, which deforms the workpiece.

In this study, an axisymmetric four-turn crimping coil was used. Compute the magnetic flux density that the coil generates when the current is enabled is the primary task. Next, this is contrasted with the magnetic flux density values generated by a solenoid with the same length and diameter.

The crimping coil can be used to calculate the magnetic field it produces by breaking down its geometry into symmetric ring elements and cylinders, assuming that the current is at its peak value and that the DC conditions are met. The magnetic flux density of the resulting coil is the vector addition of fields caused by each of these components.

Lastly, simulations are run for suitable inputs using the software packages LS-DYNA and ANSYS. The purpose of these results is validation.

CONTENTS

1. Introduction:

1.1) Electromagnetic forming

Electromagnetic forming is a high-speed or impulse-forming technique that applies Lorentz's forces to workpieces, preferably composed of a working medium with no mechanical contact and a material that is highly electrically conductive.

Electromagnetic forming is a versatile and efficient manufacturing method, particularly suitable for applications where high-speed, precision, and complex shaping are essential. It finds use in automotive, aerospace, and other industries where forming or joining metal components is a critical part of the manufacturing process.

Electromagnetic forming is based on the interaction of electric currents and magnetic fields. The result is a high-energy electromagnetic pulse that causes rapid fluctuations in the magnetic field. Lorentz forces, which are produced when the workpiece is exposed to this varying magnetic field and creates eddy currents within the material, are what cause a conductive workpiece to deform.

Several forms of electromagnetic forming are suited to particular uses, including electromagnetic sheet metal forming, magnetic pulse welding (MPW), and electromagnetic tube bulging. When compared to conventional forming techniques, electromagnetic forming offers a distinctive and effective way to shape metal components, offering benefits in terms of speed, flexibility, and tool wear.

1.2) Electromagnetic Forming principle

Electromagnetic forming (EMF) is based on the ideas of electromagnetic induction and the Lorentz force. Michael Faraday created the electromagnetic induction principle early in the 19th century, and it is now a fundamental idea in physics.

It describes how a shifting magnetic field can induce a voltage or electromotive force (EMF) in a conductor. Magnetic flow meters, electrical transformers, and AC generators all work on the principle of electromagnetic induction. This invention is important because it generates electrical energy in a circuit using magnetic fields rather than just batteries. This is the fundamental working principle of everyday appliances like motors, generators, and transformers.

The key points of the principle of electromagnetic induction are as follows:

An electromotive force (EMF) is induced in a wire whenever the magnetic field inside a closed loop of wire changes. The rate at which the magnetic flux through the loop changes determines the induced EMF.

Magnetic flux (Φ) is the product of the magnetic field (B) and the area (A) through which the magnetic field lines pass, and it is given by the formula:

$$\Phi = B \cdot A.$$

Faraday's law of electromagnetic induction mathematically is denoted as:

$$EMF = -d\Phi/dt$$

Where the induced electromotive force is EMF and $d\Phi/dt$ is the rate of changing magnetic flux with time.

2. Literature review

Author (year)	Paper title	Summary
V.Psyk et al. (2010) [1]	Electromagnetic Forming-A review	An overview of the various forms of forming, the electromagnetic forming process's principles, and an examination of the EM forming process
R. Ravaud et al. (2017) [2]	Calculation of the Magnetic Field Created by a Thick Coil	Expressions of a thick ring's magnetic field components and their simplified 3D analytical forms.
A. K. Rajak et al. (2018) [3]	Application of electromagnetic forming in terminal crimping using different types of field shapers.	FS optimization for working length, slit width, and constant FS length. FS with a single step yields the greatest radial deformation.
D. Kumar et al. (2021) [4]	The interference-fit joining of Cu-SS composite tubes by electromagnetic crimping for different surface profiles.	• For versatile loads, knurled samples work better. • For axial load, threaded samples perform better.
V. Brown et al. (2018) [5]	The Magnetic Field Along the Axis of a Short, Thick Solenoid	computation of a finite solenoid's axial magnetic field (short)
Dr. Francis Xavier Hart et al. (2018) [6]	The Magnetic Field Along the Axis of a Long Finite Solenoid	Along the solenoid's axis, the magnetic field B is either time-dependent or powered by an AC source.
Da Xu et al., Xuesong Liu et al. (2010) [7]	Calculation of electromagnetic force in the electromagnetic forming process of metal sheet	A flat spiral coil's magnetic field and its penetration into the metal workpiece

3. Advantages:

This electromagnetic forming has a lot of advantages over mechanical forming. Some of them are:

- **Minimal Tool Wear:** Unlike traditional mechanical forming processes that involve contact between tools and the workpiece, electromagnetic tube compression typically results in minimal wear on the forming tools. This can lead to longer tool life and reduced maintenance costs.

- **Contactless Process:** The forming tool and the workpiece do not come into direct physical contact during the contactless process. This feature is useful in situations where it's imperative to prevent dents, scratches, and other surface flaws.

- **Ability to Join Dissimilar Metals:** It is possible to connect tubes composed of different metals using electromagnetic tube compression. This is especially helpful in applications where it's necessary to combine various material properties for budgetary or performance constraints.

- **Precision and Control:** The process of electromagnetic forming is appropriate for producing complex shapes and tight tolerances because it provides accurate control over the applied forces. This accuracy is useful in sectors where maintaining product consistency is essential.

- **Energy Efficiency:** Since the energy is applied directly to the workpiece through electromagnetic induction, minimizing energy loss through friction, the process can be more energy-efficient than some traditional forming techniques.

- **Reduced Forming Temperature:** When compared to other forming techniques, electromagnetic forming can occasionally be done at lower temperatures. For materials that are heat-sensitive or prone to thermal distortion, this can be helpful.

4. Applications:

Because electromagnetic forming (EMF) can join and shape metal components with extremely high efficiency and precision, it has a wide range of applications in many different industries. The following are a few typical uses for electromagnetic forming:

- **Sheet Metal Forming:** In the automotive industry, EMF is frequently used to shape sheet metal parts, including structural elements and panel bodies. Without requiring a lot of tools, the process makes it possible to form complex shapes quickly and precisely.

- **Tube Compression:** EMF is used to enlarge or compress metal tubes. This helps in the production of parts for pipes, exhaust systems, ventilators, and other tubular structures.

- **Joining of Dissimilar Materials:** EMF is a useful tool for joining disparate materials, such as metals. This is important in applications where the performance requires the combination of materials with particular properties.

- **Projectile Forming:** EMF is applied to projectile shaping in defense applications. Aerodynamically sound shapes can be produced quickly and precisely during the forming process, improving performance.

- **Aerospace Components:** In the aerospace industry, EMF is used to join components, especially when producing lightweight and structurally optimized parts.

- **Metalworking and Fabrication:** EMF is used in general metalworking and fabrication processes to form and shape metal components for a variety of uses, improving the manufacturing process' accuracy and efficiency.

5. Setup:

In order to shape or join metal components, electromagnetic forming (EMF) setup requires the use of specialized equipment to generate and control electromagnetic forces. The particular elements of the configuration may change depending on the intended use and result.

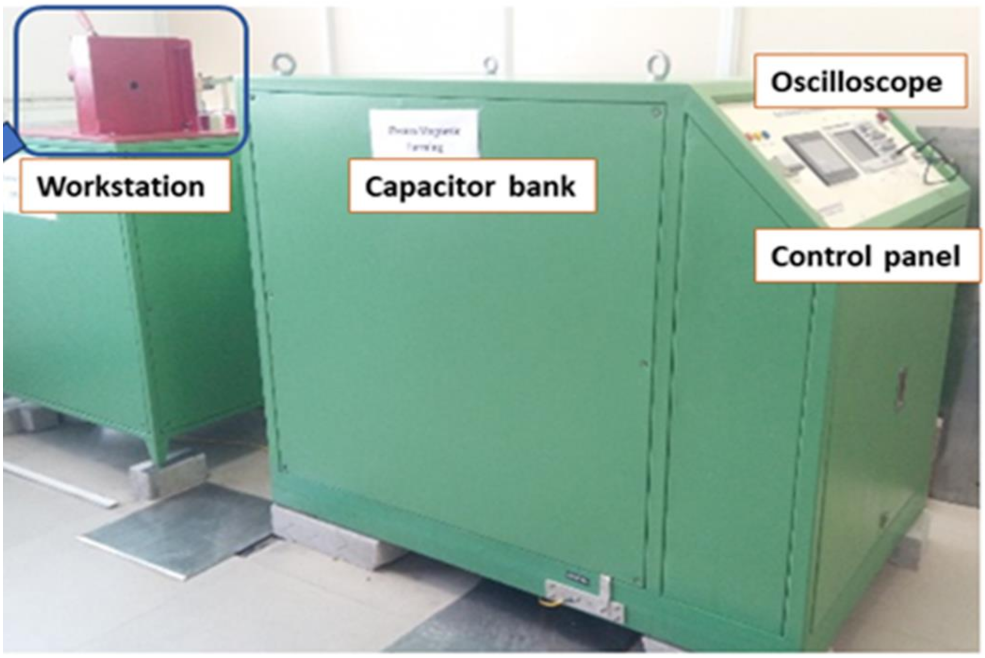

Fig 1 : An Electromagnetic forming machine

5.1) Capacitor bank: Typically, the procedure starts with a bank of capacitors, frequently made up of high-energy capacitors. These capacitors are designed to store electrical energy, which will be quickly released to produce a strong current pulse.

5.2) Pulse Generator: The controlled and quick release of the capacitors' stored energy is the job of a pulse generator. This results in a brief, high-voltage electrical pulse.

5.3) Control Panel: For precisely timing and controlling the energy discharge from the capacitors, a control panel is essential. It makes sure that the electromagnetic forces are applied precisely when needed to form or join in the desired way.

5.4) Oscilloscope: An oscilloscope, a tool for tracking and analyzing electrical signals over time, can offer vital information about the functionality and properties of an electromagnetic system.

5.5) Workstation: The workstation is the place where forming takes place. It consists of the coil which results in a magnetic field, a workpiece a field shaper to amplify the field, and fixtures to hold the setup.

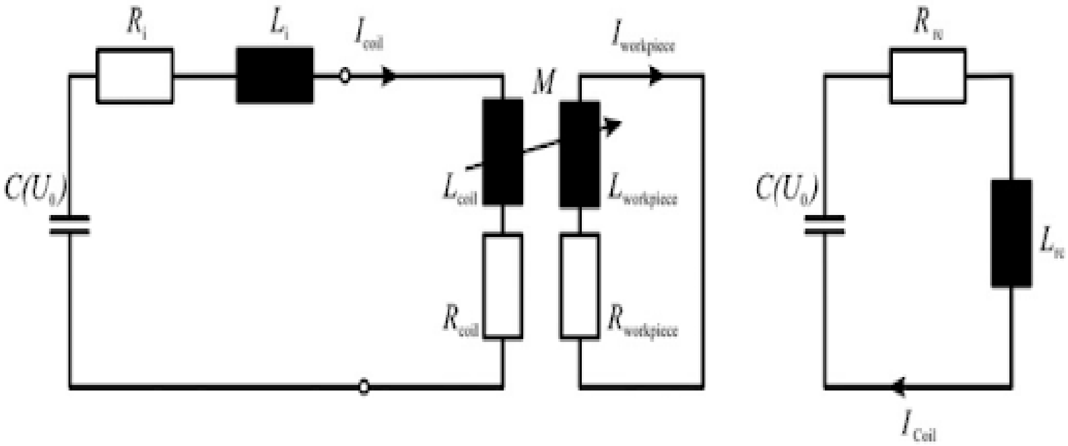

Fig 2 : Circuit of Forming machine

5.6) Process: The process starts with the creation of a magnetic field that is changing quickly. High-energy capacitors are usually discharged via an inductor or coil to accomplish this. The metal workpiece positioned inside or close to the coil experiences electric currents when the magnetic field shifts. We refer to these currents as eddy currents. The metal workpiece is filled with closed loops of circulating eddy current. According to Lenz's law, the vector direction of these circulating currents will oppose the magnetic field change that induced in them.

Strong electromagnetic forces are created when the true magnetic flux from the coil reacts with the induced magnetic flux created by eddy currents. The workpiece is subject to these forces, which result in movement or deformation. The desired forming or joining of the metal workpiece is caused by the electromagnetic forces that arise from the interaction of magnetic fields and eddy currents. This can involve procedures like welding, bending, stretching, and compressing.

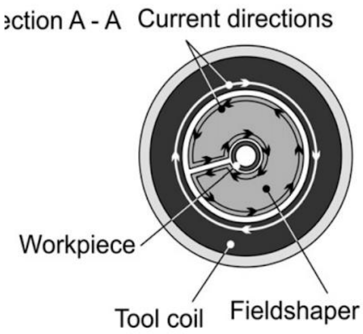

Fig 3 : Current directions in coil, workpiece and field shaper

The electromagnetic forces act on the metal workpiece, causing deformation or movement. The intensity and distribution of these forces are crucial in shaping the workpiece according to the desired outcome. Thus, the electromagnetic forces are harnessed to achieve various forming or joining processes. This can include bending, stretching, compressing, or welding the metal workpiece.

It is therefore possible to compress or expand hollow profiles, to shape and join flat or three-dimensionally formed sheet metal, and to carry out cutting operations. Forming limits can be extended for several materials because of extraordinary strain rates and high velocities when compared to traditional reversible processes. Different needs of this forming are met by relying on the configuration and design of the coil's geometry, forming of initially performed three-dimensional or flat sheet metals, as well as crimping and bulging of hollow profiles.

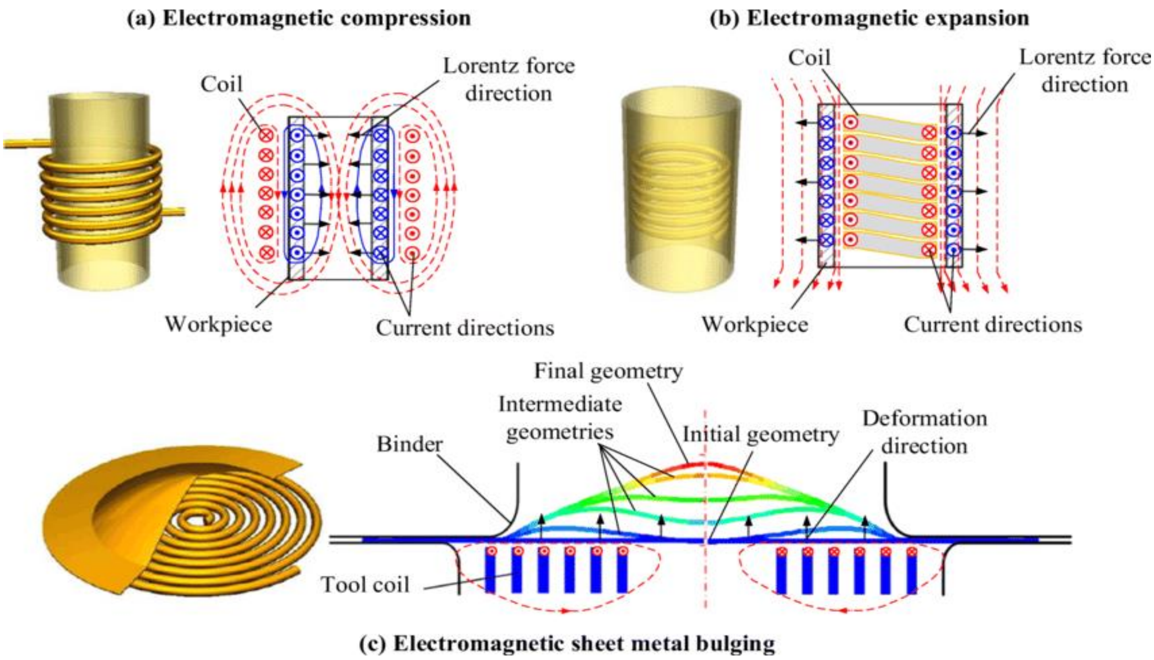

Fig 4 : Different types of forming

5.7) Types of forming:

These three distinct process variations allow for the differentiation of various coil types used in the electromagnetic forming process. The workpiece is enclosed by the coil during tube compression, but in the expansion setup, the opposite is true. Flat coils are used in electromagnetic sheet forming. In this case, the thickness of the sheet can reach 5 mm and the formed workpiece's area can range from 10−4 to 0.02 m2. sheets or large tubes must be processed using a device with a higher capacity charging energy because the chargeable energy depends on the forming area.

6. Electromagnetic Crimping:

6.1) Introduction

Electromagnetic crimping or tube compression is the process of forming in which hollow tubes of highly conductive materials are compressed or crimped radially inward. The workpiece generally consists of two pieces. A hollow tube and a target rod over which the hollow tube is crimped. This setup of the workpiece is placed in the coil. A field shaper is used around the workpiece which is made of paramagnetic and electrically conductive material. This enhances the field generated by the coil and produces stronger eddy currents workpiece.

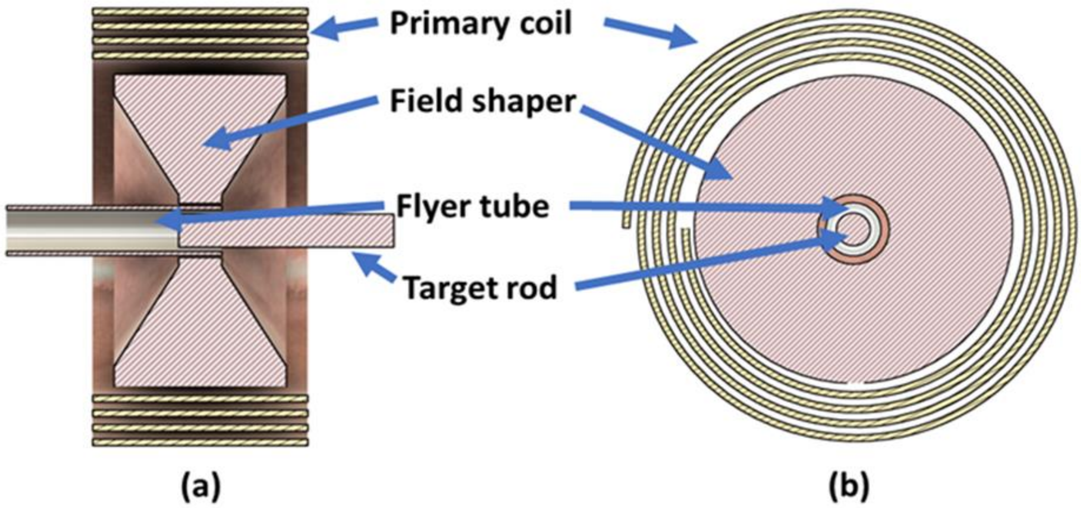

Fig 5 : (a) Vertical cross-section of setup, (b) Horizontal cross-section of the setup

6.2) Process analysis of electromagnetic crimping

A Target-oriented dimensioning of this forming process necessitates an understanding of the relevant parameters of the process along with their interactions and relationships with one another. Determining the loads acting and the deformation results of the workpiece is one crucial element. The loads acting are determined by the many variables that fall into the categories of workpiece, machine, and tool parameters. Important machine characteristics are the charging energy, ringing frequency, inner resistance, inner inductance, and capacity.

Calculating the acting loads According to Lorentz (1895), the magnetic field density B and the current density J can be used to evaluate the volume forces F acting on the workpiece.

$$F = J \times B$$

The current density's radial component equals the negative derivative of the magnetic flux strength H concerning the r as radius, as indicated, but ignores the component which is directed in the orientation of the thickness of the workpiece.

$$J = -\partial H / \partial r$$

The product of the magnetic field strength and permeability yields the magnetic flux density. One can compute forces acting radially on Fr workpiece which is tubular using

$$Fr = \mu H \, (\partial H / \partial r)$$

The workpiece's volume forces can be mathematically converted into virtual surface forces, or what is known as magnetic pressure p. The corresponding inner and outer radii γ_i and γ_0 of the tube can be used as integral limits to find the complete pressure on the workpiece.

$$p(r, t) = \int_{\gamma_0}^{\gamma_i} F(r,t)dr = 12\big(Hgap(t) - Hpen(t)\big) \text{ where}$$

Hpen is the penetrated magnetic field and Hgap is the magnetic field in the gap between coil and the workpiece.

6.3) Field shaper

A part or device intended to regulate and shape the electromagnetic field during the compression process may be called as a "field shaper" in the context of electromagnetic tube compression. The objective is to influence the deformation or compression in a desired way by optimizing the distribution of the electromagnetic forces applied to the tube. This could improve the tube compression process' accuracy and effectiveness.

Here's how a field shaper might be relevant in electromagnetic tube compression:

- Optimizing Force Distribution
- Reducing Unwanted Deformation
- Enhancing Precision in Tube Forming
- Adapting to Varying Tube Geometries

Higher current densities and stronger fields result from concentration areas that are typically much smaller than the outside surfaces of field shapers. The concentration area is the inner surface of the field shaper. This magnetic field will result in an extra flow of current through the workpiece in the concentration area, shielding the magnetic field. But as soon as the currents begin to flow, Lorentz forces begin to act on each component because the workpiece, the field shaper, and the coil are both made of conductive material. These so-called Lorentz forces cause the workpiece to deform when the subsequent stresses attain the flow stress.

7. Approach of the multiple methods to find the magnetic field at different points on the coils.

In this analysis, magnetic fields due to two different coils are estimated at their centers and their boundaries. For this, a crimping coil and a solenoid of equal dimensions are considered.

7.1) Crimping coil.

Fig 6 : Crimping coil

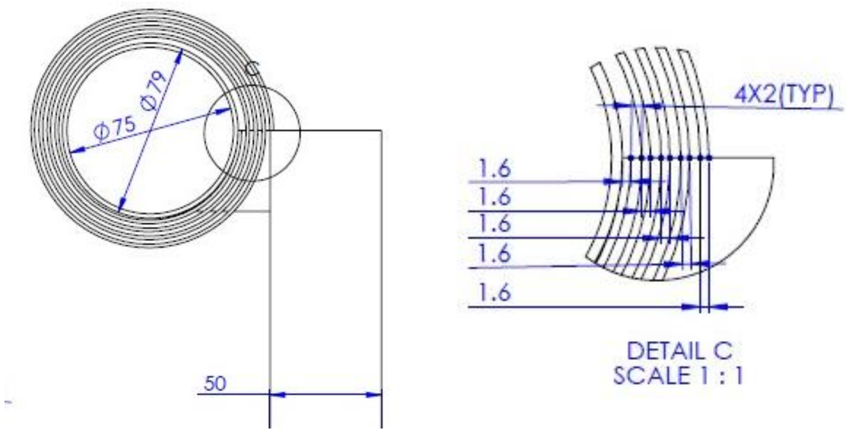

Fig 7 : Dimensions of crimping coil

7.1.1) Field of a cylinder using similar approach of field for ring element:(axial point only)

Assumptions: The coil which has four turns is assumed to be a combination of four concentric cylinders. The thickness of the coil is neglected.

The field for individual cylinders is calculated and then the resulting field is obtained by adding fields due to all cylinders vectorially. First, the field due to the individual cylinder is calculated by assuming ring elements all over the cylinder and then integrating it all over the surface.

Field due to the ring element on the axis is given by: $\frac{\mu R^2 I}{2(R^2+Z^2)^{\frac{3}{2}}}$

$$\text{Current density} = \; J = \frac{1}{2}$$

$$dB = \frac{\mu}{I} \; \frac{R^2 dI}{2(R^2+x^2)^{\frac{3}{2}}}$$

$$\mathrm{B} = \int_{\frac{-1}{2}}^{1/2} dB = \frac{\mu \mathrm{Jl}}{2\sqrt{\mathrm{R}^2 + (\frac{1}{2})^2}}$$

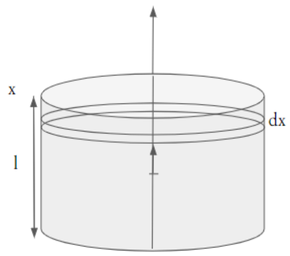

Fig 8 : Ring elements in a cylinder

In this, the four turned coil is assumed to be a combination of four different cylinders . Field due to individual cylinder is calculated seperately and then added at last . The resulting field is assumed to be approximately equal to that of coil. When the current is assumed to be 75,000 ampere, the resulting field was around 3.8 tesla at the center and 2.8T at the periphery

7.1.2) Field of a thick coil in axial and radial direction

In this method, the same concentric cylinders were assumed, but the thickness of the cylinders significantly considered.

Expressions of the Magnetic Field Components of a thick ring and their reduced 3D analytical forms are derived.

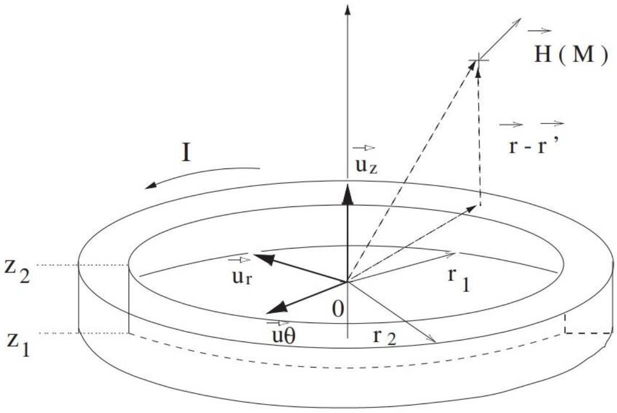

Fig 9 : Thick element from a cylinder

In this approach, the thickness of the coil is considered significantly. Field due to each thick coil is calculated at the centre and at the periphery of the coil. The total of all the fields resulting from each thick cylinder is the resulting field.

The radial and axial field for such coil is formulated as:

$$H_r(r,z) = \frac{j}{4\pi}\int_{r_1}^{r_2}\int_{\theta_1}^{\theta_2}\int_{z_1}^{z_2} \frac{(z-\tilde{z})\cos\left(\tilde{\theta}\right)\tilde{r}d\tilde{r}d\tilde{\theta}d\tilde{z}}{\left(r^2+\tilde{r}^2-2r\tilde{r}\cos\left(\tilde{\theta}\right)+(z-\tilde{z})^2\right)^{\frac{3}{2}}}$$

$$H_z(r,z) = \frac{j}{4\pi}\int_{r_1}^{r_2}\int_{\theta_1}^{\theta_2}\int_{z_1}^{z_2} \frac{\left(\tilde{r}-r\cos\left(\tilde{\theta}\right)\right)\tilde{r}d\tilde{r}d\tilde{\theta}d\tilde{z}}{\left(r^2+\tilde{r}^2-2r\tilde{r}\cos\left(\tilde{\theta}\right)+(z-\tilde{z})^2\right)^{\frac{3}{2}}}$$

The resulting field was found out to be 7.72T at the center and 10.7 at the periphery of the coil.

7.1.3) Field for an archimedean spiral coil.

In this approach, the crimping coil radius is varied according to the Archimedean spiral radius ($r=a+b\theta$). Field due to the thin strip of the spiral is calculated and then added all over the length of the coil.

Assumptions: The thickness of the coil is disregarded. The coil's cross-section is regarded as an Archimedean spiral coil. The coil's entire length is increased by the field resulting from each strip.

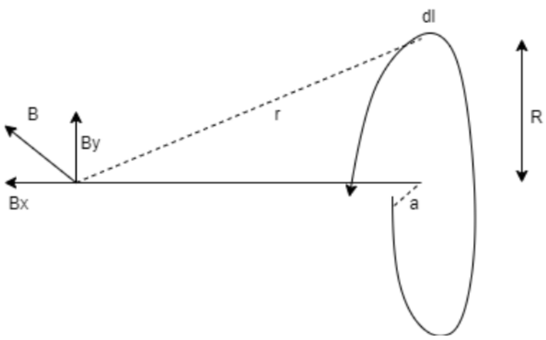

Fig 10: Spiral element from crimping coil

minimum radius = a,

maximum radius = b,

length of the coil = l,

B is the net field.

The field on the axis for a spiral element is given by:

$$\frac{\mu i}{4\pi b}\left[\left(\ln(a+b\theta+0.8)\left(\sqrt{a+b\theta}\right)^2+a^2\right)-\frac{a+b\theta}{\left(\sqrt{a+b\theta}\right)^2+a^2}\right]$$

The resulting field was found to be 3.9T at the centre.

7.2) SOLENOID

7.2.1) Field at the periphery of the coil on the top/bottom side

A Solenoid of the same length of crimping coil(50mm), thickness 10mm, and same inner radius(79mm) is considered for this. The total number of turns in the coil is 5.

$\phi_1 and\ \phi_2$ are the angles formed at the point where the magnetic field is to be found by either end of the coil.

$$B_{solenoid} = \frac{1}{2}\left(\sin\phi_1 - \sin\phi_2 \right) \frac{\mu NI}{l}$$

$$B = \frac{1}{2}\sin\left(\frac{\pi}{2}\right)\frac{\mu NI}{l} \qquad \left\{\phi_1 = \frac{\pi}{2},\ \phi_2 = 0\right\}$$

$$B \simeq 3.69T$$

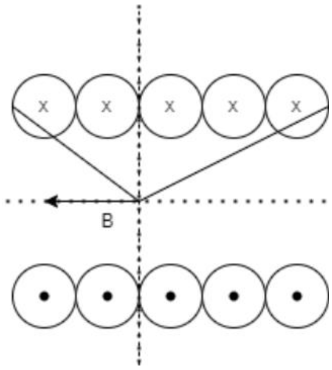

Fig 11 : cross-section of solenoid

7.2.2) Field at axial point of a finite solenoid

This approach is specifically for the axial magnetic field value of a finite length solenoid. The mean radius of the coil is considered. Z is the axial distance.

i= 75000A;

n=5 turns,

l= 50 mm(length of the coil)

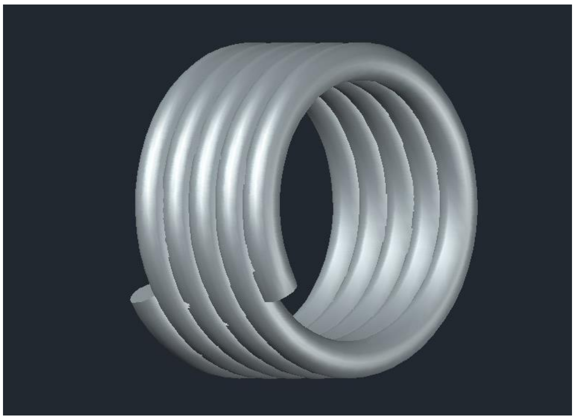

Fig 12 : A solenoid

The field for any point on the axis is given by:

$$
\begin{aligned}
B_z &= \frac{\mu_0 n I R^2}{2} \int_{-l/2}^{l/2} \frac{dz'}{\left[(z-z')^2 + R^2\right]^{3/2}} \\
&= \frac{\mu_0 n I R^2}{2} \frac{z'-z}{R^2\sqrt{(z-z')^2+R^2}} \Big|_{-l/2}^{l/2} \\
&= \frac{\mu_0 n I}{2} \left[\frac{(l/2)-z}{\sqrt{(z-l/2)^2+R^2}} + \frac{(l/2)+z}{\sqrt{(z+l/2)^2+R^2}} \right]
\end{aligned}
$$

When the axial distance is zero, i.e, z=0, the resultant field was B = 5.0387T.

The magnetic field at the boundary of the coil at z=25mm is B = 3.6T.

8.Software's used

8.1) Validation through ANSYS:

8.1.1) Crimping coil:

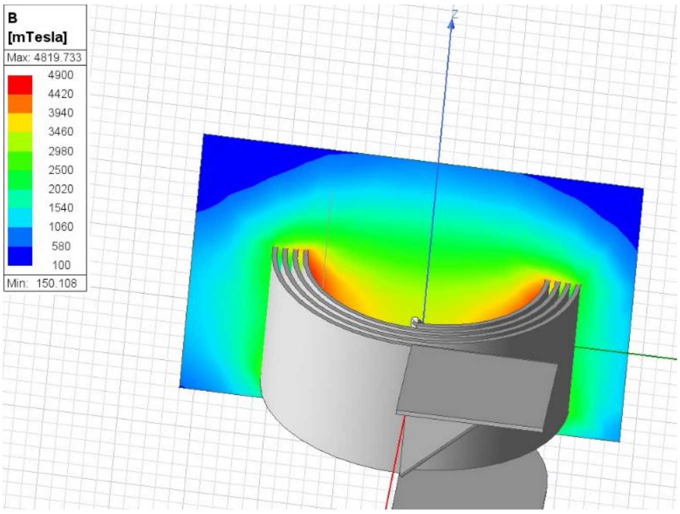

Fig 13 : Magnetic field for sectional plane view

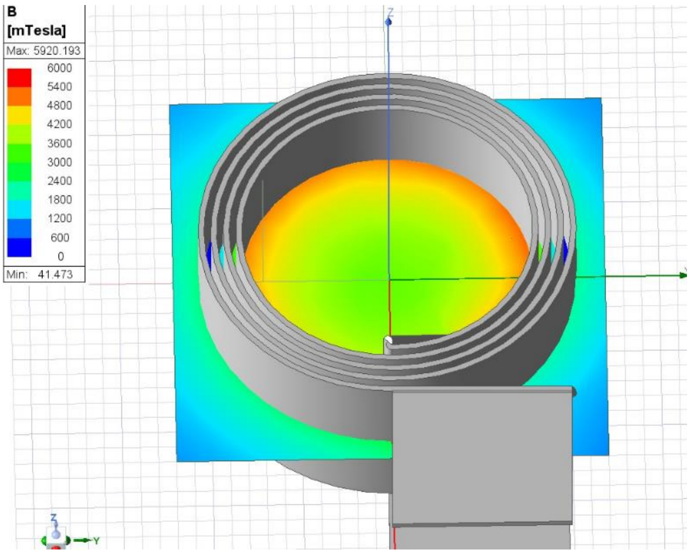

Fig 14 : Magnetic field in horizontal section plane view

8.1.2) Solenoid:

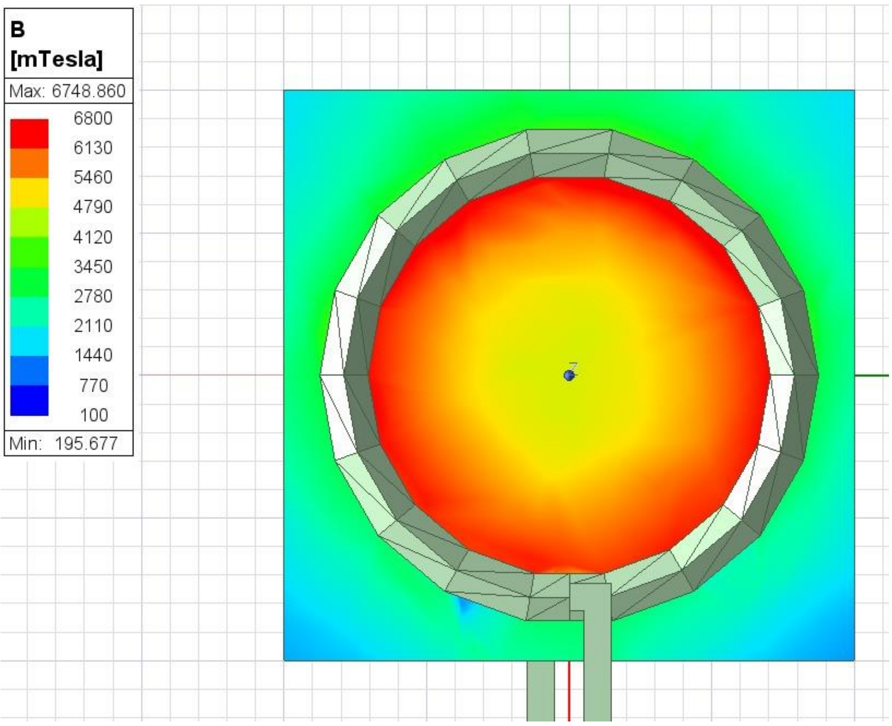

Fig 15 : Magnetic field in a solenoid (top view)

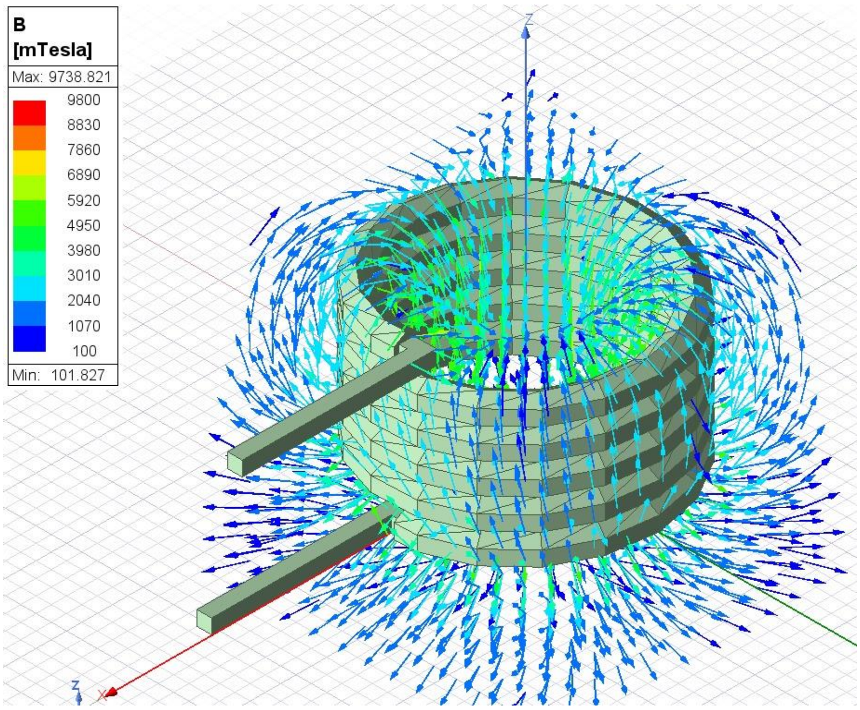

Fig 16 : Magnetic vector field lines of a solenoid

8.2) **Simulation using LS – DYNA:**

The software is employed in metal forming simulations, including processes such as stamping, forging, and extrusion. LS-DYNA can model large plastic deformation and predict the final shape of formed components.

The steps involved in processing simulation are:

1. IN ls prepost create a mesh model of the coil, workpiece, field shaper with proper dimensions.
2. Set boundary for the fieldshaper and the coil and create set_segment for input and output of the coil.
3. Create respective part ID and material ID's for all the parts
4. Define the following keywords properly with suitable values
    - Contact
    - Control
    - Define
    - Database
    - Element
    - Em
    - Hourglass
    - Initial
    - Keyword
    - Mat
    - Node
    - Part
    - Section
    - Set
    - Title
5. After assingning all the values run the simulation in LS run
6. Open the generated D3plot in prepost and see the forming happening in the given time period with various physical quantities.

7. After running the simulation in LS-DYNA, you would typically use LS-Post to analyze and visualize the results. LS-Post is the post-processing tool in LS-DYNA that allows you to examine various physical quantities, deformations, stresses, and other relevant information from the simulation.
8. If the simulation results do not match the desired forming behavior or if issues are identified, you may need to make adjustments to the simulation parameters, material properties, or other input values.
9. Make iterative changes and re-run the simulation until satisfactory results are achieved.

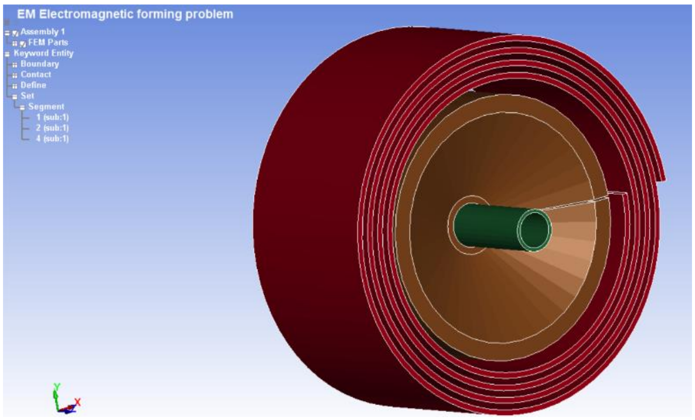

Fig 17: Front view consisting coil, field shaper, and tube in workpiece.

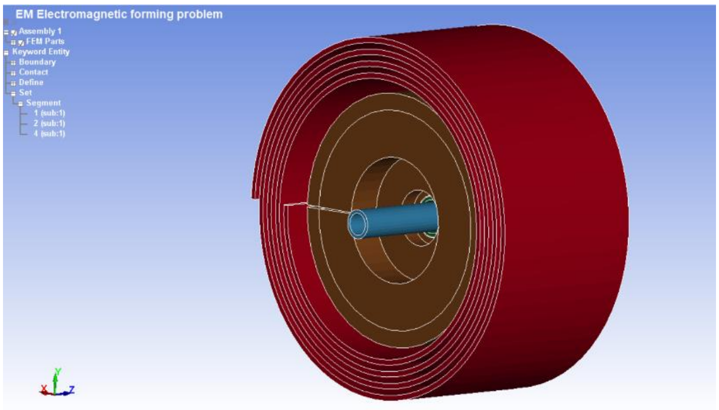

Fig 18 : rear view consisting coil, field shaper, target rod

9.Future scope :

- Finding more accurate ways to calculate the field of the crimping coil.
- Simulating LS-DYNA and find out various parameters like velocity, force, stress, magnetic pressure, displacement of the workpiece, acceleration for the process of electromagnetic crimping
- Validating analytical analysis of the coil with the simulation reu;t values in LS-DYNA.
- Experimentation on the basis of simulation values.
- Validate the simulation results by comparing them to experimental data if available. This helps ensure the accuracy and reliability of the simulation.
- Verify that the simulation adequately captures the physical phenomena and behaviors expected in the metal forming process.

REFERENCES

[1] Francis Xavier Hart; The Magnetic Field Along the Axis of a Short, Thick Solenoid. *Phys. Teach.* 1 February 2018; 56 (2): 104–106. https://doi.org/10.1119/1.5021438

[2] Chih-Ta Chia, Ya-Fan Wang; The Magnetic Field Along the Axis of a Long Finite Solenoid. *Phys. Teach.* 1 May 2002; 40 (5): 288–289. https://doi.org/10.1119/1.1516383

[3] Da Xu, Xuesong Liu, Kun Fang, Hongyuan Fang; Calculation of electromagnetic force in the electromagnetic forming process of metal sheet. *J. Appl. Phys.* 15 June 2010; 107 (12): 124907. https://doi.org/10.1063/1.3437201

[4] Ebrahimi, N., Schimpf, P., & Jafari, A. (2018). Design optimization of a solenoid-based electromagnetic soft actuator with a permanent magnet core. Sensors and Actuators A: Physical, 284, 276-285. https://doi.org/10.1016/j.sna.2018.10.026

[5] Psyk, V., Risch, D., Kinsey, B., Tekkaya, A., & Kleiner, M. (2011). Electromagnetic forming—A review. Journal of Materials Processing Technology, 211(5), 787-829. https://doi.org/10.1016/j.jmatprotec.2010.12.012

[6] Nassiri, A., Zhang, S., & Kinsey, B. (2022). An accelerated analytical method for predicting workpiece velocity and displacement during electromagnetic forming. *Journal of Manufacturing Processes*, *82*, 64-77. https://doi.org/10.1016/j.jmapro.2022.07.054

[7] Rajak, A.K., Kore, S.D. Application of electromagnetic forming in terminal crimping using different types of field shapers. *J Mech Sci Technol* **32**, 4291–4297 (2018). https://doi.org/10.1007/s12206-018-0827-z

[8] Suzuki, H., Murata, M., & Negishi, H. (1987). The effect of a field shaper in electromagnetic tube bulging. *Journal of Mechanical Working Technology*, *15*(2), 229-240. https://doi.org/10.1016/0378-3804(87)90036-2

[9] Li, H., Zhang, D., Zhang, Y., Wei, D., Yang, H., Liu, Y., Ma, J., Chu, Z., & Zhan, M. (2021). Macro-/Meso-Scaled Forming of Tubular Structures/Components. *Encyclopedia of Materials: Metals and Alloys*, 371-400. https://doi.org/10.1016/B978-0-12-819726-4.00039-9