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A two stage finite element analysis of electromagnetic forming of perforated aluminium sheet metals

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Abstract

Interest in electromagnetic forming of sheet metals for automotive applications has been growing in recent years, due to its potential to form aluminium and other low formability materials. Further, to achieve the aim of weight reduction, some components are made of perforated sheet metals. The aim of this paper is to study and analyse the two stage electromagnetic forming of perforated aluminium sheet metals with the help of Finite Element method. The Electromagnetic force on the sheet is calculated using Ansys Emag by changing the parameters in current density, gap between coil and sheet, the coil thickness. The force is calculated for nine combinations of the three parameters. Taguchi orthogonal array is used to find the best combination of parameters. Also optimization of parameters controlling the electromagnetic force is found out using ANOVA technique. The obtained force is applied on the sheet and the corresponding deformation of the sheet is obtained using Ansys Structural.

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Keywords : Electromagnetic forming, finite element analysis, magnetic force, perforated sheet metal;

Nomenclature

E	Young's modulus (MPa)
ν	Poisson's ratio
ρ	Density (kg/mm^3)
μ	Magnetic permeability
r	Resistance (Ohm-mm)

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1. Introduction

In the electromagnetic forming (EMF) process, a transient electrical pulse of high magnitude is sent through a specially designed forming coil by a low-inductance electric circuit. During the current pulse, the coil is surrounded by a strong transient magnetic field. The transient nature of the magnetic field induces current in a nearby conductive workpiece that flows opposite to the current in the coil. The coil and the workpiece act as parallel currents through two conductors to repel one another. The force of repulsion can be very high, equivalent to surface pressures on the order of tens of thousands of Newton per square meter. Thin sheets of material can be accelerated to high velocity in a fraction of a millisecond. This pressure is large enough to deform the work metal beyond the elastic yield strength; thus produces the permanent deformation of the work piece at very high strain rates. At present, a significant emphasis on developing reliable numerical methods for the simulations of the process is demanded for the profitable industrial application of EMF. A comprehensive overview of the process and its applications are given by Anter El-Azab et al. [1] and Psyk et al. [2]. A recent interest in understanding the EMF of metals has been stimulated by the desire to use more aluminum in automobiles. The high workpiece velocities achievable using this forming method enhances the formability of materials such as aluminum.

1.1 Basic working principle

An impulse electromagnetic system is used in various applications such as compression or expansion of metal tubes, forming of flat sheets; e.g. panels in automotive industries, welding and many other applications, however the identical working principle has been employed in all the applications. Depending on the geometry of the work-piece to be modified, the geometries of the coils and other parts of the impulse electromagnetic forming system could be different in shape. The Fig.1 shows the schematic representation of the system with flat sheet as work-piece [3].

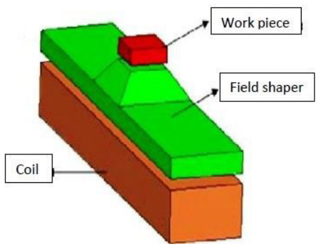


Fig. 1. EM forming system applied with a field shaper for flat model (Bahmani et al. 2009)

2. Methodology

2.1 A 3D model of the electromagnetic forming process

The environment is modelled in CATIA. The 3D model of the system is shown in fig. 2. It includes a flat rectangular coil and work piece surrounded by air region. The workpiece used is a perforated aluminium sheet [4] of dimension 50mm x 50mm x 1.5 mm with a regular 6mm x 6mm square perforation pattern. The dimension of each square is 2mm x 2mm.

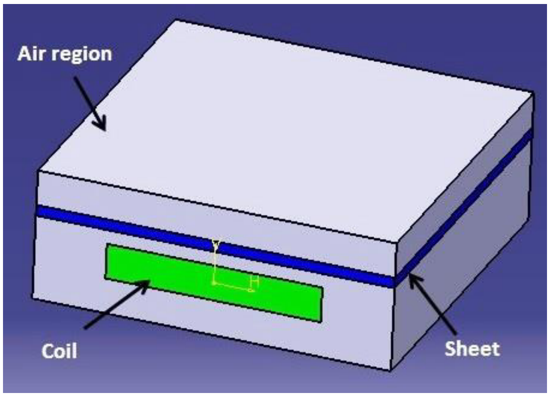


Fig. 2. 3D setup of the Coil, Sheet and Air region

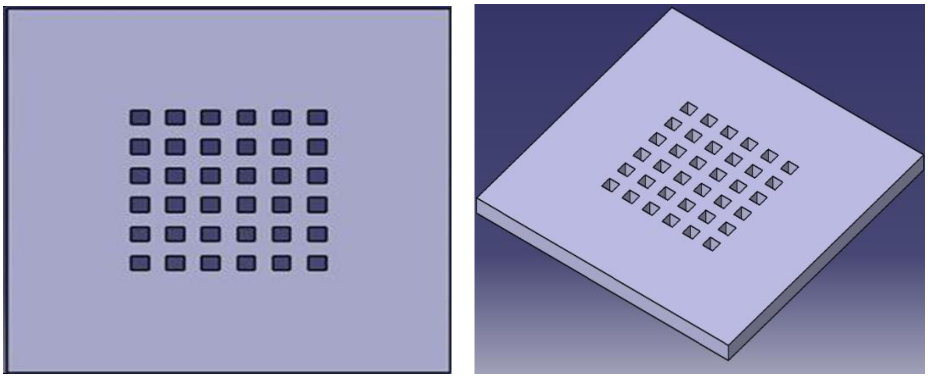


Fig 3. (a) CAD model of perforated aluminium sheet-2D view ; (b) CAD model of perforated aluminium sheet-3D view

2.2 Electromagnetic analysis using FEM

The model from CATIA is imported to ANSYS for Finite Element analysis. The material properties of the workpiece and coil are listed in Table 1.

Table 1. Material properties

	E (MPa)	ν	ρ (kg/mm^3)	μ	r (ohm-mm)
Aluminium workpiece	70000	0.35	2.7e-6	1.002	2.77e-5
Copper coil	110000	0.34	8.96e-6	0.999	1.72e-5
Air region	-	-	-	1	-

The 3D electromagnetic simulation [5,6] and calculation of electromagnetic force is carried out by using ANSYS Emag. The finite element model is shown in Fig. 4. In order to propagate the magnetic field generated by the coil, the coil, sheet and the air region are all meshed with SOLID97 element. The flux parallel boundary condition is given over the outer surface area. When the current density is applied to the coil, magnetic field is induced in the surrounding region. The electromagnetic force distribution generated by coil is shown in fig 5.

Three major parameters that influence the distribution of electromagnetic force, namely, current density, gap between coil and workpiece and coil thickness are chosen for optimization analysis. Three levels of above parameters are chosen, such as current density of 900A/m^2, 1000 A/m^2 and 1100 A/m^2,coil thickness as 3mm,4mm and 5mm, gap between coil and workpiece as 1mm,1.5mm and 2mm. L9 orthogonal array is chosen. The results of magnetic force for the L9 combinations are listed in Table 2. Optimum combination of parameters that gives the best result are found out using MINITAB software experimental planning.

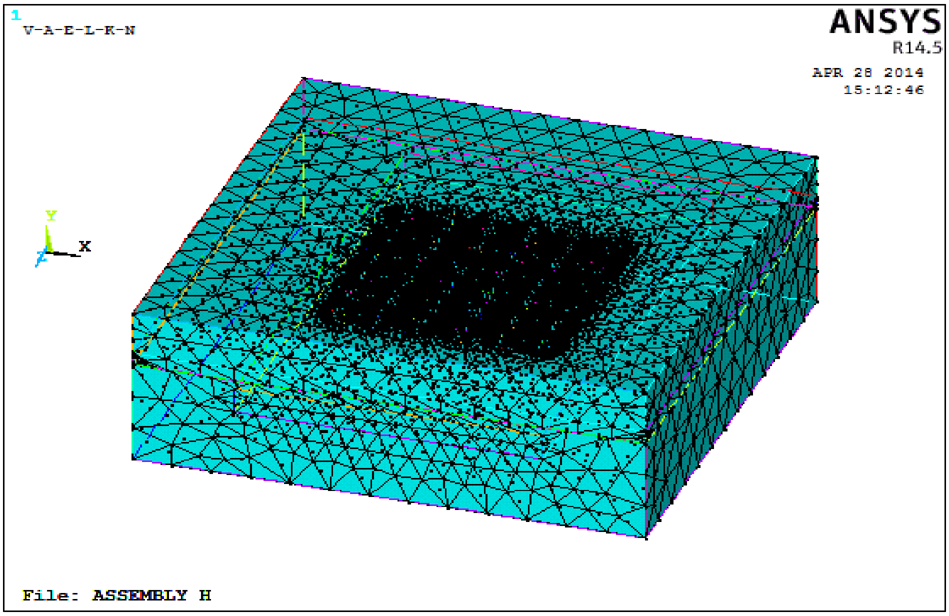


Fig.4. Meshed model of the assembly

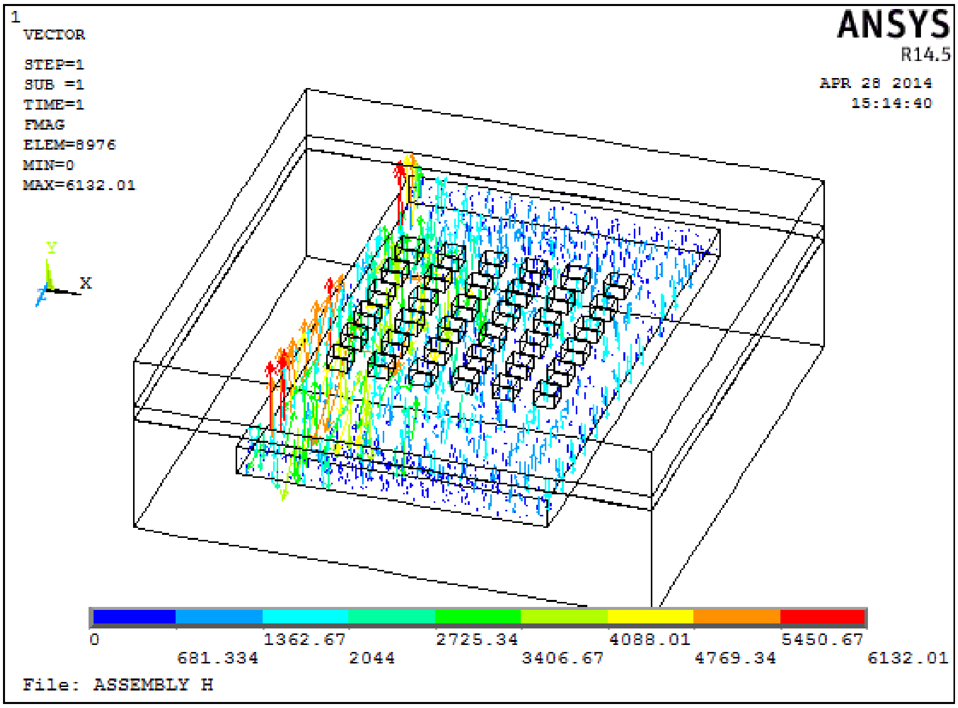


Fig. 5. Electromagnetic force generated by the coil for experiment no. 1

Table 2. Magnetic force for L9 combinations

Experiment no.	Current density (A/m^2)	Gap (mm)	Coil thickness (mm)	Magnetic force(N)
1	900	1	3	6132
2	900	1.5	4	7192.4
3	900	2	5	8323.03
4	1000	1	4	9032.94
5	1000	1.5	5	9755.37
6	1000	2	3	7594.2
7	1100	1	5	13035.7
8	1100	1.5	3	10159
9	1100	2	4	11299

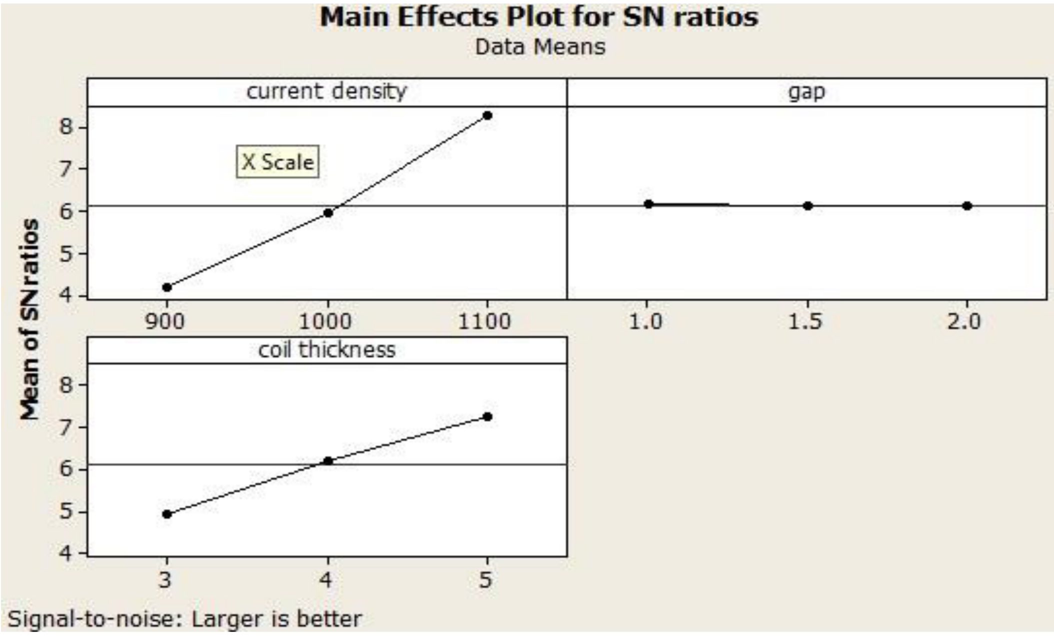


Fig.6. Mean S/N ratio graph for magnetic force

In this work, it is the-larger-the-better case, which means that the highest magnetic force would be the ideal case. The obtained results were plotted in an S/N response graphical form as shown in fig. 6. The contour plot in fig.7 helps to identify the higher magnetic force when the coil thickness and current density value are higher.

The different magnetic force equations (1) is obtained with regression analysis as,

Magnetic force = - 16568 + 21.4 current density - 328 gap + 1205 coil thickness .... (1)

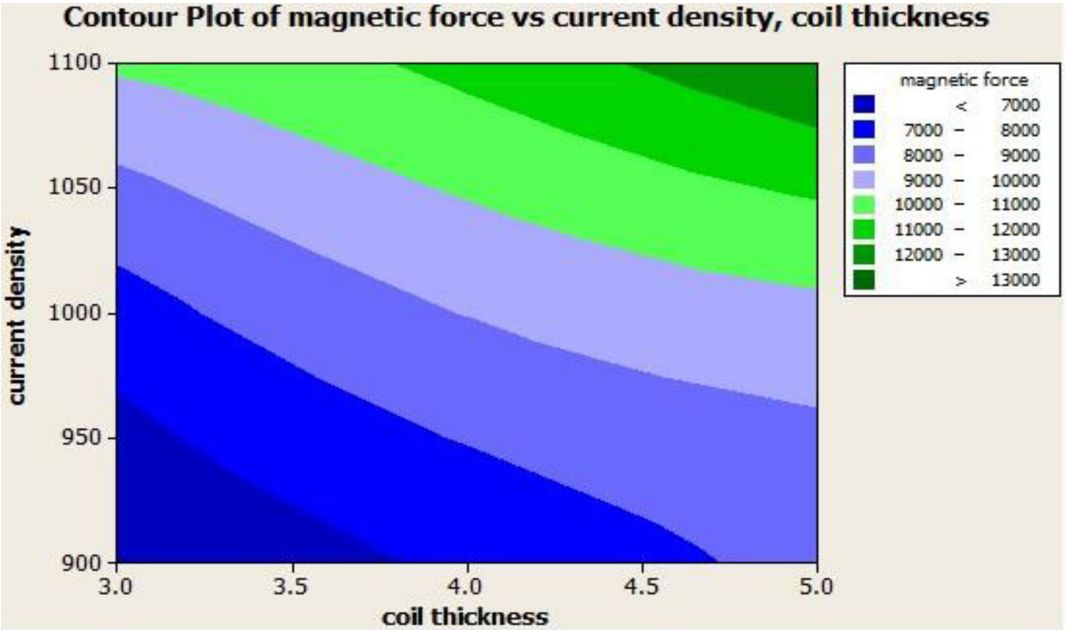


Fig.7. Contour plot for variation in magnetic force with current density and coil thickness

2.3 Structural analysis

In this structural analysis, high carbon steel base die having circular pocket is fixed. The perforated sheet is kept on the base die and pressure is applied on the sheet with the help of hemispherical die having surface contact with the sheet. The magnetic forces (F) calculated by electromagnetic analysis module are applied in the form of pressure to perforated aluminium sheet metal with the help of a die to calculate deformation of sheet. The 3D CAD model shown in fig. 8 is drawn in CATIA and imported to ANSYS workbench. The material properties of sheet and dies are listed in table 3.

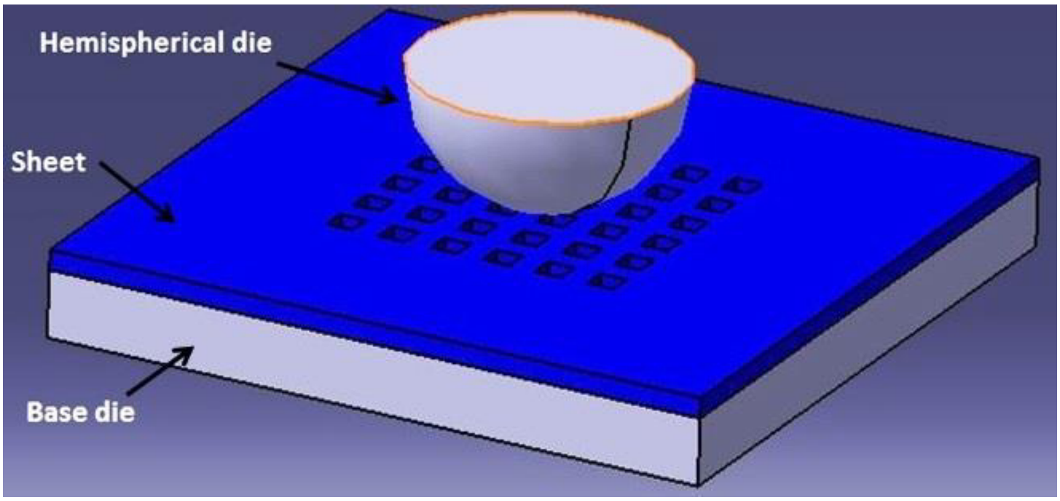
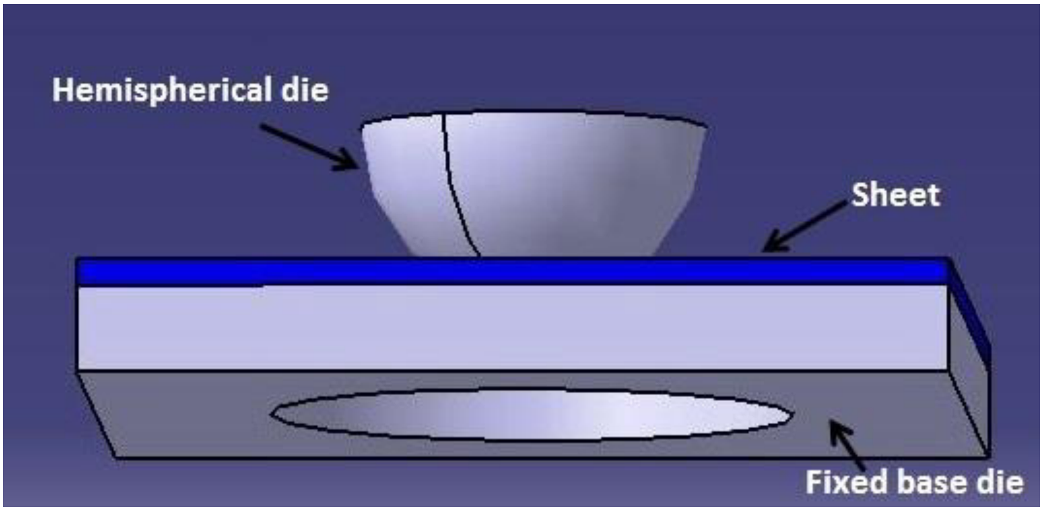


Fig. 8(a) 3D CAD model of sheet, base die and hemispherical shaped die



8 (b) View of base die with circular pocket

Table 3. Material properties

	Material	E (MPa)	N	ρ (kg/mm^3)
Aluminum sheet	Aluminium	70000	0.35	2.7e-6
Hemispherical die	high carbon steel	210000	0.3	7.8e-6
Base die	high carbon steel	210000	0.3	7.8e-6

The deformation values for the nine combinations considered according to L9 orthogonal array are listed in Table 4. The mode of deformation due to the first and last combinations are shown in figure 9.

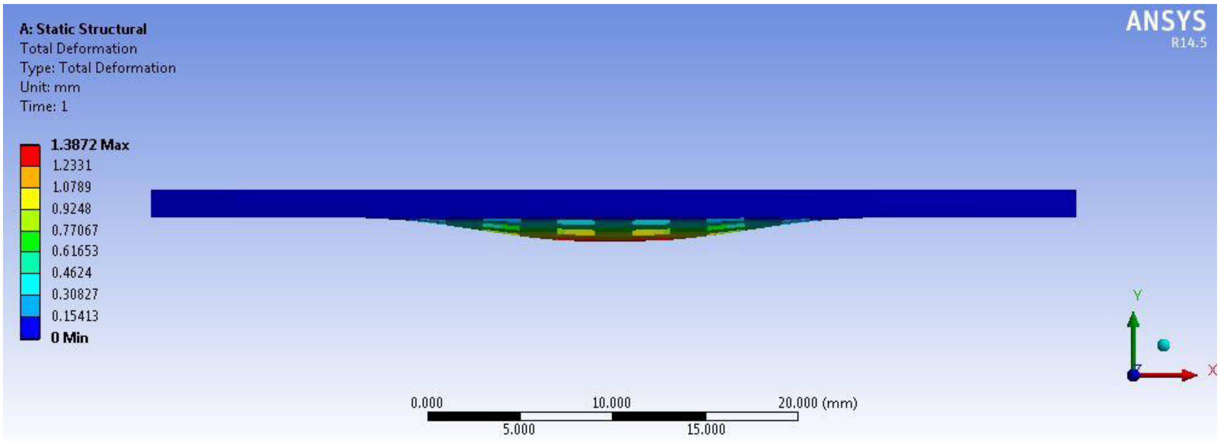


Fig.9(a). Deformed model of the sheet for first combination

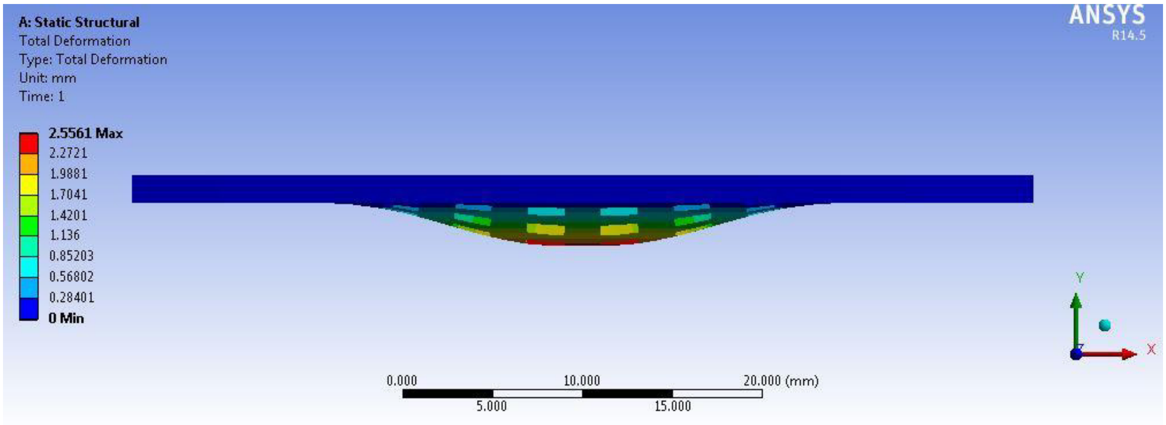


Fig.9(b). Deformed model of the sheet for last combination

Table 4. Deformation results

Expt no.	Current density (A/m^2)	Gap (mm)	Coil thickness (mm)	Magnetic force (N)	Pressure (N/mm^2)	Deformation (mm)
1	900	1	3	6132	8.675	1.3872
2	900	1.5	4	7192.4	10.17	1.627
3	900	2	5	8323.03	11.77	1.8829
4	1000	1	4	9032.94	12.77	2.0435
5	1000	1.5	5	9755.37	13.80	2.2068
6	1000	2	3	7594.2	10.74	1.7179
7	1100	1	5	13035.7	18.44	2.9488
8	1100	1.5	3	10159	14.37	2.2982
9	1100	2	4	11299	15.98	2.5561

In this work, it is the-larger-the-better case, which means that the largest deformation would be the ideal case. The obtained results were plotted in an S/N response graphical form as shown in fig. 10.

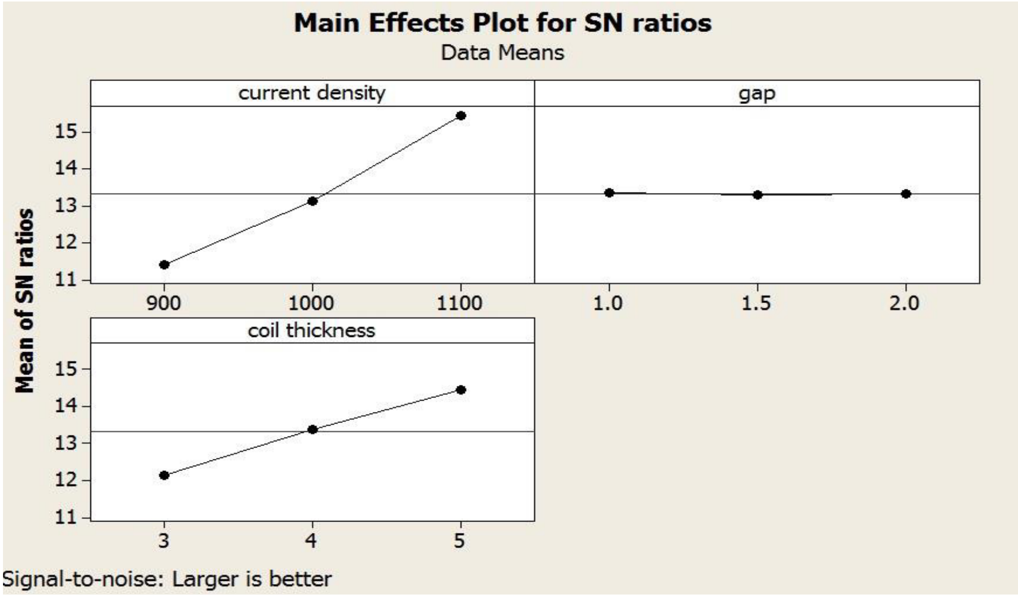


Fig.10. Mean S/N ratio graph for deformation

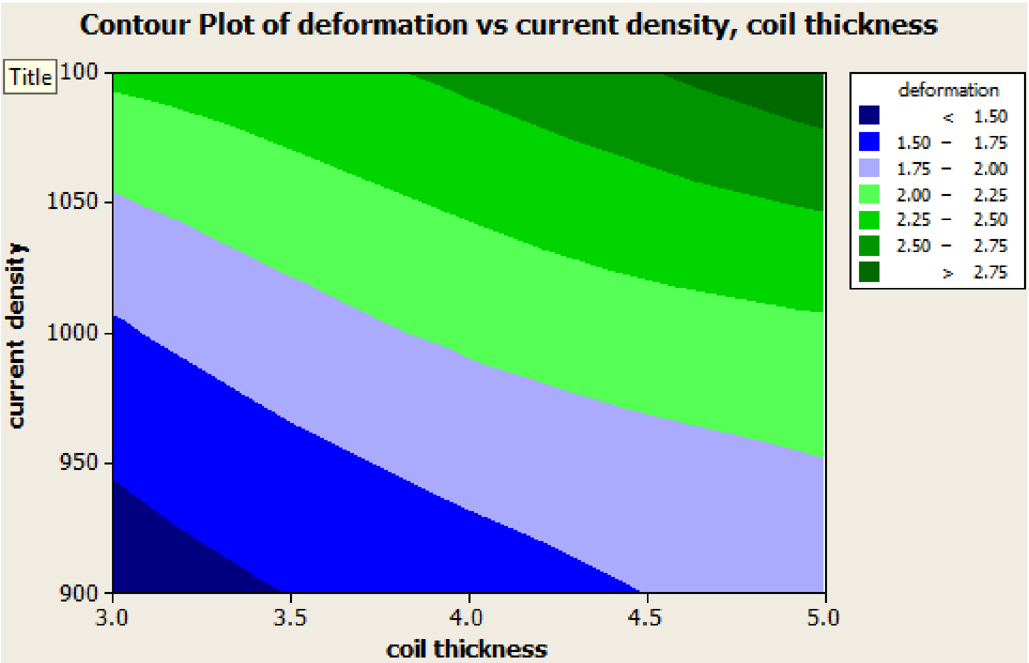


Fig.11. Contour plot for variation in deformation with current density and coil thickness

The contour plot shown in fig. 11 helps to identify that the highest deformation happens when the coil thickness and current density value are higher. The different deformation equation obtained with regression analysis is given in equation (2).

Deformation = - 3.75 + 0.00484 current density - 0.0742 gap + 0.273 coil thickness .... (2)

3. Conclusion

The overall goal of this work is to study the forming behavior of the perforated alumiunim sheets when it is subjected to EMF process and also to perform a parametric study on some of the process parameters that controls the magnetic force and deformation of the sheet. Experimental studies can be very expensive, whereas numerical analyses are comparatively economical and allow wider range of parameters to be investigated in short period of time. From the above analysis, it is clear that the amount of current density applied and coil dimensions play vital role in calculation of magnetic force and deformation of the sheet. Also the gap between coil and sheet has negligible influence on generation of magnetic force and deformation.

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