Efficient Coil Design by Electromagnetic Topology Optimization for Electromagnetic Sharp Edge Forming of DP980 Steel Sheet

M. K. Choi[1], H. Huh[1*], M. H. Seo[2], Y. Kang[2]

[1] School of Mechanical, Aerospace and Systems Engineering, KAIST, Daejeon, Korea
[2] Steel Solution Center, POSCO, Incheon, Korea
[*]Corresponding author. Email: hhuh@kaist.ac.kr

Abstract

This paper proposes a design method of the tool coil by topology optimization for the electromagnetic sharp edge forming process. Topology optimization is an approach that optimizes material configuration in a given domain to meet the design requirements. The design problem for the tool coil is defined as enhancing efficiency of the forming process and optimization problem is set to be maximization of the Lorentz force induced on the tool coil. A new topology optimization formulation based on the numerical methods for electromagnetism using FEM and BEM is developed for maximization of the Lorentz force. Optimum design of the tool coil is obtained by the topology optimization using the element density approach. The optimized result is compared with other coils which have different configurations to show the effectiveness of the proposed method. The idea of applying topology optimization to the design of the tool coil is successful and this formulation deals effectively for the optimization problems.

Keywords

Coil design, Topology optimization, Electromagnetic sharp edge forming

1 Introduction

Auto industries recent trend is to develop lightweight vehicles for both improvement of both efficiency and crashworthiness of auto-body with the use of advanced high strength steels (AHSS). DP980 steel is one of the AHSS materials with ultimate tensile strength of higher than 980 MPa. However, the application of DP980 steel sheet to auto-body is limited with conventional deep drawing processes due to its poor formability in many cases of manufacturing of automotive parts.

Electromagnetic forming (EMF) is one of the innovative forming methods to improve the formability of a material. There are advantages of EMF with a material of poor formability. In EMF, the workpiece is accelerated to high strain rates so the mechanical properties and the formability of the workpiece material can be improved compared to the quasi-static ones (Psyk et al., 2011). In addition, forming force can be applied locally and it is possible to perform EMF in hard-to-reach areas by utilizing a suitable tool coil (Psyk et al., 2011). EMF can be combined with conventional deep drawing for sharp edge forming process which consists of pre-forming by conventional deep drawing and making a sharp corner radius of a workpiece electromagnetically.

Many researchers have conducted investigations on the feasibility of the electromagnetic sharp edge forming process over the last years. Vohnout (1998) showed that combination of higher strains and more complex geometries of a door inner and a hood part can be realized using combined deep drawing and electromagnetic calibration. Psyk et al. (2007) studied sharpening of a feature on an automotive stamping and found that the process was feasible. Imbert and Worswick (2011) showed that hybrid conventional/electromagnetic forming process using a specially designed coil could be successful in corner filling process for aluminum alloy sheet parts.

Most of the research works about electromagnetic sharp edge forming process are, however, limited to the application of aluminum alloys. In general, electromagnetic forming is suitable for materials with a high electrical conductivity. The application of DP980 steel sheet to EMF seems to be challenging because DP980 steel sheet has low electrical conductivity and very high flow stress. Choi et al. (2014) developed a method for optimization of electromagnetic sharp edge forming process of DP980 steel sheet and the process was feasible. However, they suggested that the efficiency of the electromagnetic energy delivery would have to be enhanced to accommodate industrial settings.

In order to enhance the efficiency of the electromagnetic energy delivery, optimum coil design is necessary. The coil is an important component of any EMF process since it delivers the electrical energy to form the workpiece. However, only a small part of the charging energy is used for the plastic deformation resulting in a comparable bad efficiency of the EMF process. Thus the optimum design of the tool coil is conducted to enhance the efficiency of the forming process.

This paper proposes a design method of the tool coil by topology optimization for the electromagnetic sharp edge forming process. Topology optimization is an approach that optimizes material configuration in a given domain to meet the design requirements. In this paper, design requirement for the tool coil is defined as enhancing the efficiency of the forming process and optimization problem is set to be maximization of Lorentz force induced in the tool coil. In order to solve the optimization problem, a new topology optimization formulation is developed for Lorentz force maximization. Optimum design of the tool coil is obtained using the topology optimization. Then the optimized result is compared with the other coils which have different configurations to show the effectiveness of the proposed method.

2 Optimization Formulation

2.1 Problem Description

Electromagnetic sharp edge forming of DP980 steel sheet where optimum coil will be applied is described in Fig. 1. Conventional square cup drawing with a punch radius of 30 mm is conducted for pre-forming of the process. Then electromagnetic sharp edge forming is applied to the pre-formed workpiece to obtain a sharp edge with a punch radius of 10 mm (Choi et al., 2014). In order to form the sharp edge of DP980 workpiece with the electromagnetic sharp edge forming process, efficient tool coil is necessary due to low electrical conductivity and high flow stress of DP980 steel sheet.

The design objective of the tool coil is to find an optimal configuration of the tool coil that maximizes the efficiency of the process. The efficiency of the process is defined as the ratio of the deformation energy to the stored electrical charging energy. The deformation energy in this process is determined by the Lorentz force in the radial direction. Thus, the optimum tool coil which maximizes the Lorentz force in the radial direction will be obtained.

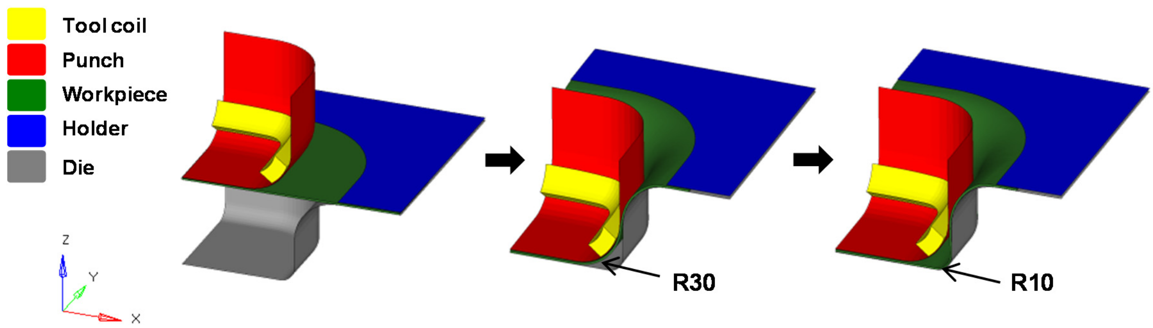

Figure 1*: Schematic of electromagnetic sharp edge forming of DP980 steel sheet*

2.2 Numerical Methods for Electromagnetism

The optimization formulation for the Lorentz force maximization is based on the numerical methods used in LS-DYNA EM module (L'Eplattenier et al., 2008). Governing equations of electromagnetism are Maxwell's equations. Maxwell's equations in terms of scalar and vector potential with Eddy current approximation can be expressed as follows:

$$\nabla \cdot (\sigma \vec{\nabla} \phi) = 0 \tag{1}$$

$$\sigma \frac{\partial \vec{A}}{\partial t} + \vec{\nabla} \times (\frac{1}{\mu} \vec{\nabla} \times \vec{A}) + \sigma \vec{\nabla} \phi = \vec{j}_s \tag{2}$$

where ϕ is the electric scalar potential, $\vec{A}$ is the magnetic vector potential, σ is the electrical conductivity, μ is the magnetic permeability and $\vec{j}_s$ is the source current density.

The potential equation can be solved by a finite element method using differential forms elements (Ren and Razek, 1996). There are four forms of basis function called 0-forms, 1-forms, 2-forms and 3-forms, defined on the solid hexahedral element. Equation (1) is projected on the 0-forms basis functions, W^0, which are scalar basis functions that have a gradient. Equation (2) is projected on the 1-forms basis functions, $\vec{W}^1$, which are vector basis functions that have a curl. The weak formulations are obtained by applying the boundary conditions and integration by part as follows:

$$\int_\Omega \sigma \vec{\nabla}\Phi \cdot \vec{\nabla} W^0 d\Omega = 0 \tag{3}$$

$$\int_\Omega \sigma \frac{\partial \vec{A}}{\partial t} \cdot \vec{W}^1 d\Omega + \int_\Omega \frac{1}{\mu} \vec{\nabla} \times \vec{A} \cdot \nabla \times \vec{W}^1 d\Omega = -\int_\Omega \sigma \vec{\nabla}\Phi \cdot \vec{W}^1 d\Omega + \int_\Gamma \frac{1}{u} \left[\vec{n} \times \left(\vec{\nabla} \times \vec{A} \right) \right] \cdot \vec{W}^1 d\Gamma \tag{4}$$

where $d\Omega$ is an element of volume Ω, Γ is the boundary of volume Ω and $\vec{n}$ is the outer normal to the boundary. After decomposing the scalar and vector potential on the 0-forms and 1-forms basis function, the finite element equations can be derived as follows:

$$\mathbf{S^0}(\sigma)\phi \ = \ 0 \tag{5}$$

$$\mathbf{M^1}(\sigma)\frac{\partial a}{\partial t} + \mathbf{S^1}(\frac{1}{\mu})a \ = \ -\mathbf{D^{01}}(\sigma)\phi + \mathbf{S}a \tag{6}$$

with the stiffness matrix of the 0-forms $\mathbf{S^0}$, the mass matrix of the 1-forms $\mathbf{M^1}$, the stiffness matrix of the 0-forms $\mathbf{S^1}$ and the derivative matrix of the 0-1-forms $\mathbf{D^{01}}$. The finite element matrices can be found in L'Eplattenier et al., 2008.

The last term $\mathbf{S}$, the outside stiffness matrix, cannot be directly computed. It can be computed from a definition of a BEM system. The BEM system is used for solving equations in the air. In order to compute the last term of the FEM system, a surface current $\vec{k}$ is introduced on the surfaces of the conductors from the Biot−Savart equation.

$$\vec{A}(x) = \frac{\mu_0}{4\pi} \int_\Gamma \frac{1}{|x-y|} \vec{k}(y) \, dy \tag{7}$$

Using new technique proposed by Ren and Razek (1990), Equation (8) can be expressed as follow:

$$\vec{n} \times (\vec{\nabla} \times \vec{A})(x) = \frac{\mu_0}{2} \vec{k}(x_0) - \frac{\mu_0}{4\pi} \int_\Gamma \frac{1}{|x-y|^3} \vec{n} \times [(\vec{x} - \vec{y}) \times \vec{k}(y)] \, dy \quad \text{where } x \to x_0 \in \Gamma \tag{8}$$

After discretization of vector potential with 1-form basis functions and surface current with 1-form surface basis functions $\vec{V}^1 = \vec{n} \times \vec{W}^1$, the BEM system equations can be derived as follows:

$$\mathbf{P}k = \mathbf{D}a \tag{9}$$

$$\mathbf{S}a = \mathbf{Q}k = \mathbf{Q_s}k + \mathbf{Q_d}k \tag{10}$$

with the BEM matrices which can be found in L'Eplattenier et al., 2008.

The FEM system Equation (6) is coupled with the BEM system Equation (9) and (10). Time integration is done with implicit backward Euler method. The global system equations are expressed as follows:

$$\mathbf{P}k_{n+1}^{t+1} = \mathbf{D}a_{n}^{t+1} \tag{11}$$

$$\left[\mathbf{M^1}(\sigma) + dt\mathbf{S^1}(\frac{1}{\mu})\right]a_{n+1}^{t+1} = \mathbf{M^1}(\sigma)a^t - dt\mathbf{D^{01}}(\sigma)\phi^{t+1} + dt\mathbf{Q}k_{n+1}^{k+1} \tag{12}$$

Equation (5) is solved only when a voltage is imposed with the Dirichlet condition. Equation (11) is solved using a pre-conditioned gradient method and Equation (12) is solved using a direct solver.

Once the scalar potential and the vector potential have been determined, the Lorentz force can be computed. The Lorentz force is cross product of the current density $\vec{j}$ and the magnetic flux density $\vec{B}$. In terms of vector potential, the Lorentz force generated on the workpiece can be expressed with the topological derivative matrix as follows:

$$\vec{F} = \vec{j} \times \vec{B} = \sigma\left(-\frac{d\vec{a}_i}{dt}\right) \times \left(-\mathbf{T}^{12}\vec{a}_i\right) \tag{13}$$

2.3 Topology Optimization Formulation

In order to obtain optimal configuration of the tool coil by topology optimization, the element density approach is adopted. For electromagnetic topology optimization, the electric conductivity is assumed to vary from 0 to σ_0 with element density x as follows:

$$\sigma = \sigma_0 f(x) = \sigma_0 \cdot x^p \tag{14}$$

where σ_0 is the electric conductivity of a material and p is the penalization power. In addition, the BEM system is utilized for numerical methods for electromagnetism. The boundary element determines the boundary of the conductor and air, which has importance in computation of vector potential. When the finite element of the conductor becomes close to 0, the element is regarded as air and new boundary elements might be created. Therefore, the boundary element density function is considered for every face element. When element E_1 and E_2 share a face element F, the boundary element density is expressed as follows:

$$\rho_F = \left|x_{E_1} - x_{E_2}\right| \tag{15}$$

Design variables are determined as densities of elements in the domain. The topology optimization problem for the tool coil is set with the design variables: finding the element densities of the coil domain which maximize the sum of the Lorentz force generated on the workpiece subject to the mass constraint. It is expressed as follow:

$$
\begin{aligned}
&\textit{Find}: && \vec{x} = \left[x_1, x_2, \cdots, x_j, \cdots, x_m \right]^{\mathrm{T}} \\
&\textit{Maximize} && F = \sum_{i=1}^{n} \left| \sigma\left(-\frac{d\vec{a}_i}{dt} \right) \times \left(-\mathbf{T}^{12}\vec{a}_i \right) \right| \\
&\textit{Subject to} && h(x_j) = \sum_{j=1}^{m} x_j v_j - M \le 0
\end{aligned}
\tag{16}
$$

where $\vec{x}$ is the element density vector for the coil domain, m and n is the number of elements of the coil domain and the workpiece, respectively. v_j is the volume of element j and M is the constrained mass of the coil.

The topology optimization problem is solved by the method of moving asymptotes (Svanberg, 1987) which is a gradient based optimizer. In order to use the MMA, the sensitivity analysis of the objective function and the constraint function with respect to the element density are necessary. The sensitivity of the objective function can be computed as follows:

$$
\begin{aligned}
\frac{d}{dx_j}F &= \frac{d}{dx_j}\left[\sum_{i=1}^{n} \sigma\left(-\frac{d\vec{a}_i}{dt} \right) \times \left(-\mathbf{T}^{12}\vec{a}_i \right) \right] \\
&= \sum_{i=1}^{n} \left(\sigma \frac{d}{dx_j}\left(-\frac{\vec{a}_i^{\,t} - \vec{a}_i^{\,t-1}}{dt} \right) \times \left(-\mathbf{T}^{12}\vec{a}_i^{\,t} \right) + \sigma\left(-\frac{\vec{a}_i^{\,t} - \vec{a}_i^{\,t-1}}{dt} \right) \times \frac{d}{dx_j}\left(-\mathbf{T}^{12}\vec{a}_i^{\,t} \right) \right)
\end{aligned}
\tag{17}
$$

The sensitivity of the objective function is in terms of the vector potential and the sensitivity of the vector potential. The sensitivity of the vector potential is obtained from the global system equations using the FEM and BEM matrices as follows:

$$
\begin{aligned}
&\frac{\partial \mathbf{M^1}(\sigma)}{\partial x_j}\frac{(a_{n+1}^{t+1} - a^t)}{dt} + \mathbf{M^1}(\sigma)\frac{\partial}{\partial x_j}\left[\frac{(a_{n+1}^{t+1} - a^t)}{dt} \right] + \mathbf{S^1}(\frac{1}{\mu})\frac{\partial a_{n+1}^{t+1}}{\partial x_j} \\
&= -\frac{\partial \mathbf{D^{01}}(\sigma)}{\partial x_j}\phi^{t+1} - \mathbf{D^{01}}(\sigma)\frac{\partial \phi^{t+1}}{\partial x_j} + \mathbf{Q}_s(\rho)\frac{\partial k_{n+1}^{t+1}}{\partial x_j} + \mathbf{Q}_d(\rho)\frac{\partial k_{n+1}^{t+1}}{\partial x_j} + \frac{\partial \mathbf{Q}_s(\rho)}{\partial x_j}k_{n+1}^{t+1} + \frac{\partial \mathbf{Q}_d(\rho)}{\partial x_j}k_{n+1}^{t+1} \\
&\text{where} \quad \frac{\partial \phi^{t+1}}{\partial x_j} = \mathbf{S^0(x)}^{-1}\left(-\frac{\partial \mathbf{S^0(x)}}{\partial x_j}\phi^{t+1} \right) \\
&\qquad\quad\;\; \frac{\partial k_{n+1}^{t+1}}{\partial x_j} = \mathbf{P}(\rho)^{\mathbf{-1}}\left(\mathbf{D}(\rho)\frac{\partial a_n^{t+1}}{\partial x_j} + \frac{\partial \mathbf{D}(\rho)}{\partial x_j}a_n^{t+1} - \frac{\partial \mathbf{P}(\rho)}{\partial x_j}k_{n+1}^{t+1} \right)
\end{aligned}
\tag{18}
$$

3 Coil Design Optimization

3.1 Topology Optimization of the Tool Coil

The topology optimization problem is defined for the design of the efficient tool coil. The coil domain for the electromagnetic topology optimization problem is described in Fig. 2. The gap between the tool coil and the workpiece is set to 1 mm. A part of the tool coil is considered for the coil domain since it is assumed that the tool coil has a constant cross section along the edge of the workpiece and the optimal configuration of the cross section of the tool coil is necessary for the coil design. Coil current flows through the RLC circuit connected part and the Lorentz force is generated on the workpiece. The optimal location of the Lorentz force applied to the workpiece for successful electromagnetic sharp edge forming is studied by Choi et al. (2014), and the corresponding optimal region of the workpiece is considered for the optimization problem. As for input parameters, the electrical conductivities are $5.75\times10^{7}\ \Omega^{-1}\ \mathrm{m}^{-1}$ for the tool coil and $6.99\times10^{6}\ \Omega^{-1}\ \mathrm{m}^{-1}$ for the workpiece. The RLC values of the equivalent circuit are set to be 6 mΩ, 230 nH and 380 µF, respectively and the voltage of 12 kV is imposed as a capacitor voltage. The constrained mass of the coil is set to half of mass of the coil domain.

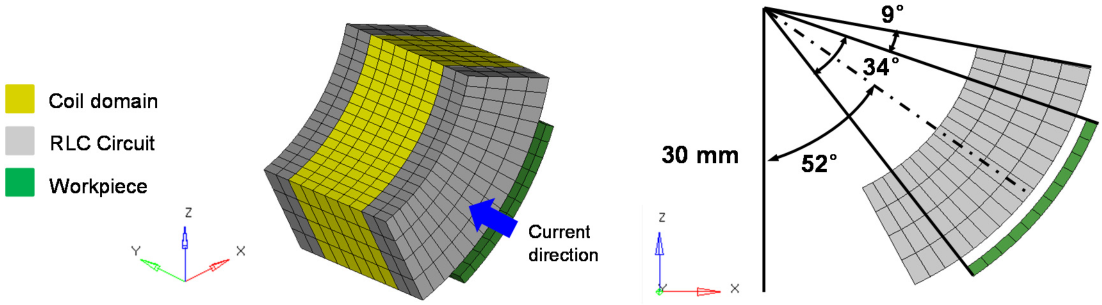

***Figure 2**: The coil domain for the electromagnetic topology optimization problem*

The optimal distribution of densities of the tool coil is shown in Fig. 3. Densities of the elements near the workpiece are higher than that of the elements far from the workpiece. The objective and constraint function values converge after 6th iteration.

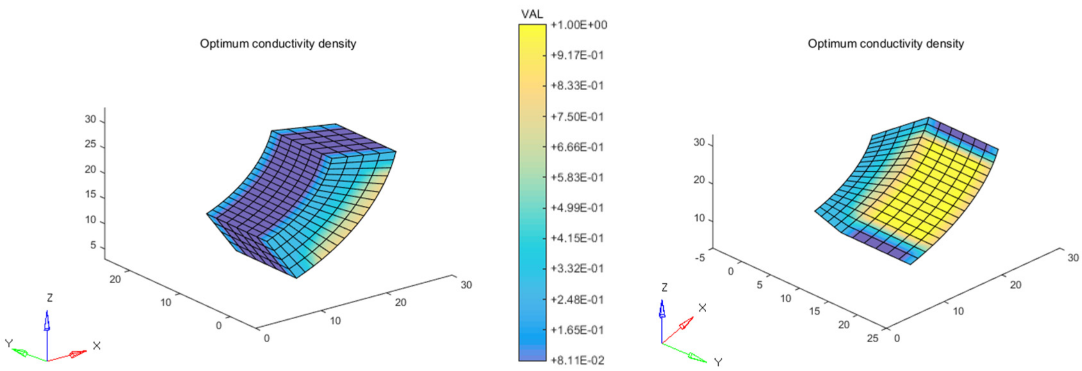

***Figure 3**: The optimal distribution of densities of the tool coil*

3.2 Efficiency of the Optimum Tool Coil

Optimal configuration of the tool coil is obtained by solving the electromagnetic topology optimization problem. Based on the optimal configuration, optimum design for efficient tool coil is obtained as shown in Fig. 4. The coil thickness is determined as 5 mm according to the constraint of cross section area since 4 kA/mm^2 is allowed for a copper conductor without overheating or mechanical damage (Kim et al, 2014). Outer radius is 29 mm which determines the gap between the tool coil and the workpiece as 1 mm.

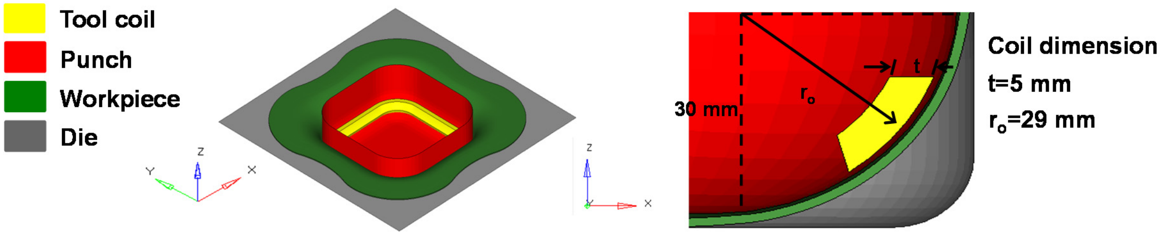

***Figure 4**: The optimum design for the efficient tool coil*

Numerical analysis of electromagnetic sharp edge forming of DP980 steel sheet is conducted to investigate the efficiency of the optimum tool coil. For the numerical analysis, LS-DYNA EM module is employed. Electromagnetic parameters described in Section 3.1 are used for input parameters of the numerical analysis. The efficiency of the optimum tool coil is compared with other coils which have different configurations. Various configurations of the tool coil are shown in Fig. 5. The dimensions of each tool coil are determined according to the constraint of cross section area.

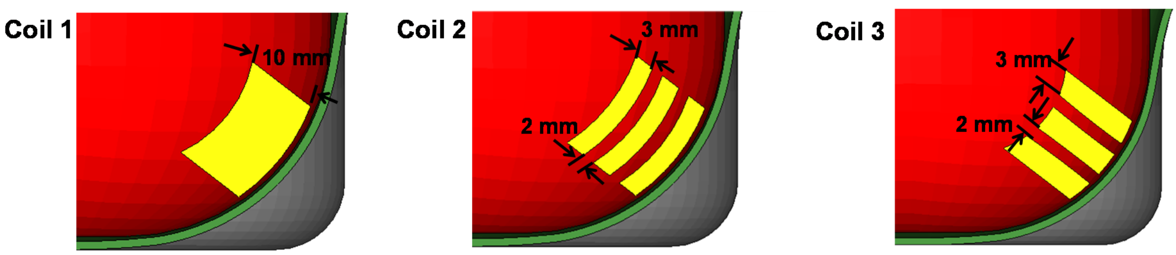

***Figure 5**: Various configurations of the tool coil for the comparison of the efficiency*

After the numerical analysis, the section profile along the x-z plane is obtained as shown in Fig. 6 with various configurations of the tool coil. It is confirmed that the amount of the deformation is largest for the optimum tool coil. The enhancement of the efficiency by the optimum tool coil appears quite significant compared with various configurations of the tool coil.

In order to investigate why the optimized coil provides efficiency improvement, distributions of the maximum current density during the process in each coil are compared as shown in Fig. 7. Unit for the current density is mA/mm^3. The current density of the optimized coil has the largest value among other coils although the resistance of the optimized coil is the largest and total current flowing through the coil is the smallest among other coils. In addition, the current density of the optimized coil is concentrated at the region which is close to the workpiece. This can lead to high induced current density and high magnetic flux density on the workpiece which is related to the Lorentz force.

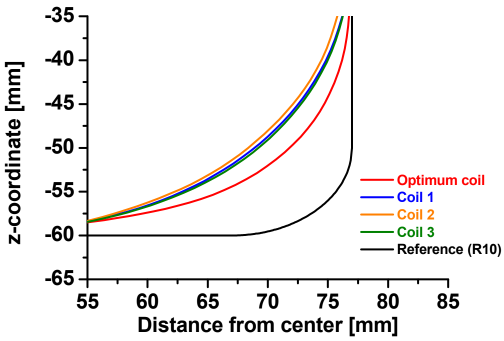

***Figure 6**: Section profile along the x-z plane with various configurations of the tool coil*

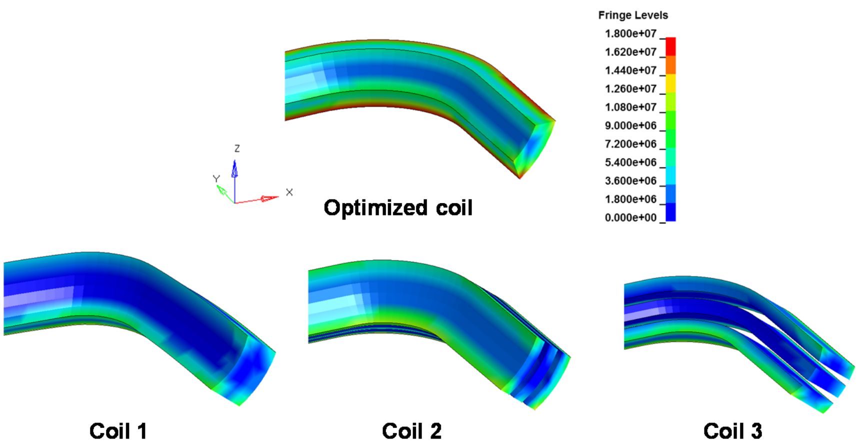

***Figure 7**: Distributions of current density with various configurations of the tool coil*

Induced current density and magnetic field on the workpiece with various configurations of the tool coil are compared as shown in Fig. 8. The result by the optimized coil is the largest and the resultant Lorentz force will also be the largest, thus the optimized coil can provide improvement of the efficiency.

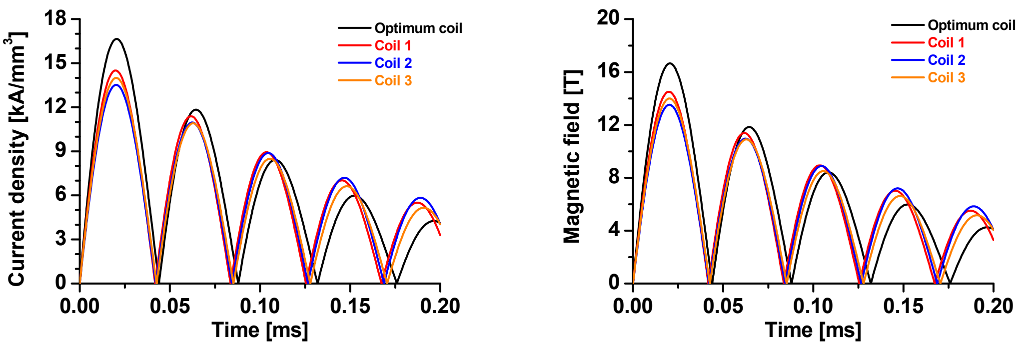

***Figure 8**: Induced current density and magnetic field on the workpiece with various configurations of the tool coil*

4 Conclusion

This paper introduces a design method of the efficient tool coil by topology optimization. Topology optimization formulation is based on the numerical methods for electromagnetism using the FEM and BEM. Topology optimization problem is defined as maximization of the Lorentz force in the radial direction. Tool coil is treated as electric conductors and the element density approach is used for representing the electric conductivity. The idea of applying topology optimization to the design of efficient tool coil is successful and this formulation deals effectively for the optimization problems.

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