Chapter 6
Simulation of a Screw Self-tapping Process

Kushagr Goyal, Sivaraman Rajan, Harish Krishnamurthy and Ravindra Venkataramu

Abstract With the ever-increasing demand to use lightweight materials in the automotive industry, automakers are keen on using plastics across their products. Plastics are predominantly held together using adhesives, screws, or snaps. Screws are promising when axial reinforcement between the components is desired. Self-tapping screws are now the preferred type, for its ease of assembly and cost. A self-tapping screw can tap its own hole as it is driven into the material. Such screws can be broadly classified into two categories: Thread-cutting screws (woods and metals) and thread-forming screws (plastics and thin metal sheets). Thread-forming screws form the threads by local deformation by displacing the material along its travel. Generation of these threads in plastic components using FE simulation is often tricky as it undergoes severe localized plastic deformations. This calls for the use of a unique FEM approach called Combined Eulerian Lagrangian (CEL), in which the screw and the plastic screw post are modeled using Lagrangian and Eulerian formulations, respectively. The Eulerian domain allows large localized deformations to accommodate plastic flow. This approach also enables the evaluation of the tightening torque in addition to the thread-formation pattern on the plastic component.

Keywords Combined Eulerian Lagrangian (CEL) · Self-tapping screw · Thread-forming and tightening torque

6.1 Introduction

The present times call for improved efficiency at a system level in pretty much every industry. One of the most important factors in improving efficiency and life of component systems is to reduce their weight. This leads to reduced inertial loads during dynamic operations and less wear and tear. The automotive industry is no different,

K. Goyal · S. Rajan · H. Krishnamurthy · R. Venkataramu (✉)
Inteva Products India Automotive Private Limited, Bengaluru, India
e-mail: RVenkataramu@intevaproducts.com

© Springer Nature Singapore Pte Ltd. 2020

C. Li et al. (eds.), *Advances in Engineering Design and Simulation*,
Lecture Notes on Multidisciplinary Industrial Engineering,
https://doi.org/10.1007/978-981-13-8468-4_6

with its focus on weight reduction. It's also a very crucial factor in enhancing the performance and dropping the overall emission levels of a motor vehicle.

With the advent of new manufacturing technologies and research on polymer plastics, it has become ever more possible to replace more and more metal components with plastics. With clever design and careful material selection, plastic components can replace the metals in several areas. The plastic components are much lighter than their metal counterparts. They can also be manufactured at a much faster rate and at a lower cost (considering larger volumes). Plastic parts also do not suffer from any type of corrosion.

However, the plastic parts usually tend to display higher sensitivity to temperature, humidity, etc. They are also more susceptible to higher levels of wear and tear. Connecting these plastic components to each other requires different processes than metal parts. One of such processes is to use a self-tapping screw for assembly. Self-tapping screws tap their own hole as they are driven into the material. There are several different designs of self-tapping screws based on their ends, as shown in the image below (Fig. 6.1).

The type of screw to be used depends upon the application, material of the components to be fastened together, availability, and cost. Here, this work deals with the Type "B" self-tapping screw. Threads are created by the process of forming or cutting depending on the material. In plastics, these screws can displace the material and "form" the threads. On the assembly line, these screws reduce the process time by reducing the number of operations required for fastening the components together.

Self-tapping screws can produce a lot of stress in a component as they are driven into the material. They also cause severe localized deformations in order to form threads. This becomes a particularly difficult problem to simulate because of the large localized deformation. The usual approach of structural simulations is found to

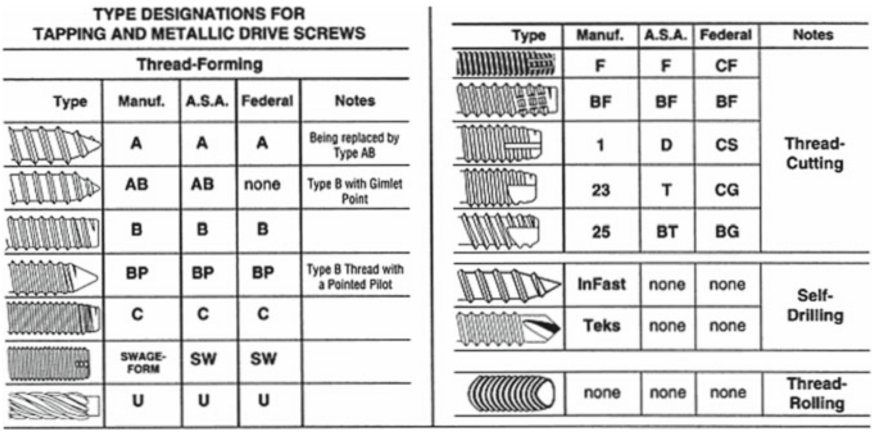


Fig. 6.1 Types of self-tapping screws

be inadequate. This calls for a unique approach for simulating self- tapping process, called the Combined Eulerian Lagrangian (CEL) approach.

6.2 Combined Eulerian Lagrangian (CEL) Approach

The most common method of modelling in finite element analysis is considered to be the Lagrangian model of the elements. This type of element formulation is easy to implement and computationally less expensive to solve [1]. Here, the nodes are coincident with the material, and therefore, under the application of load, they both move together. Furthermore, the material inside each element is fixed and cannot move in or out of the element. This allows for easy application of boundary conditions and tracking of the free surfaces.

[2] However, with all its advantages, the Lagrangian formulation does suffer from the reduced accuracy of results in simulations with large deformations/strains. There are a couple of techniques used to reduce the effect of these large deformations. One of these techniques works by locally remeshing the domain as the simulation progresses. Another technique that can be used deletes the elements based on predefined criteria. Though these techniques can help improve the accuracy of the model, they increase the simulation time as they are more computationally expensive.

The Eulerian formulation of the elements can get us around the issue of large deformation/strain. Unlike a Lagrangian mesh, here the elements don't deform themselves but the material flows through them. Since the material can flow through elements, the domain must be modeled larger than required so that no material can flow out of it; otherwise, the material that leaves the domain is no longer considered in the simulation. The basic difference between the Lagrangian and the Eulerian formulations can be visualized in the image below (Fig. 6.2).

It may be observed that since the mesh itself does not deform, it can handle large deformations easily. However, there is difficulty in tracking the free surfaces as the material boundary differs from the nodal boundary. This also makes it difficult to apply boundary conditions to the model.

Hence, here it is proposed to use the Combined Eulerian and Lagrangian (CEL) approach. Usually, this approach is used for fluid-structure interactions. It combines

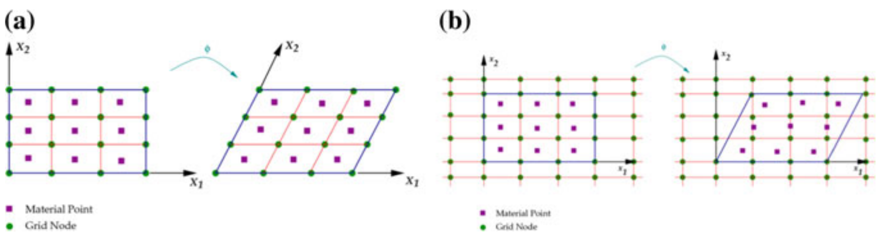


Fig. 6.2 **a** Lagrangian mesh model **b** Eulerian mesh model

both the Eulerian and Lagrangian meshes in the same model. Regions which are expected to undergo large deformation are modeled using Eulerian formulation, and the remaining regions can be modeled using Lagrangian formulation. The Eulerian mesh allows for evaluation of deformations with reasonable accuracy in the regions of interest.

6.3 Model Setup

This work deals with a plastic component which the self-tapping screw is fastened into. The screw is fastened into a hollow cylindrical part of this component called the screw post. The aim is to evaluate the fastening torque and strength and performance of this screw post during the self-tapping process. Three distinct designs of this screw post are evaluated in order to find out the design that's most suitable for self-tapping.

6.3.1 Material Model

The model setup of the simulation for this work, as it may be observed from Fig. 6.3c, considers only two components, namely the screw and the screw post. The screw is made of steel, and the screw post is made up of a plastic material. For computational efficiency and practical purpose, the screw is considered to be rigid, for there is a large difference between the stiffness of steel and plastic and marginal deformation is assumed in the screw during the self-tapping process.

Typical FEM solvers offer several material models for simulating different types of materials like metals, plastics, rubbers, etc. The choice of the material model depends upon the type of the material itself, the loading conditions, temperature, strain rate dependency, anisotropy, etc.

[3] Material nonlinearity is caused by a nonlinear relationship between the stress and strain after the yield limit is reached. Beyond the yield limit, some part of the material will start yielding and the stress starts to respond in a nonlinear fashion to applied strain. This is what causes the change in the stiffness of the component, and it depends upon a material behavior called Elasto-plastic behavior. For the work presented here, this material model is assumed for the screw post (Fig. 6.4).

Such materials exhibit a characteristic called work or strain hardening. This increases the yield stress of the material when it is taken in the plastic region. This increase in strength is eventually followed by softening if the external load keeps increasing, and ultimately leads to the failure of the material.

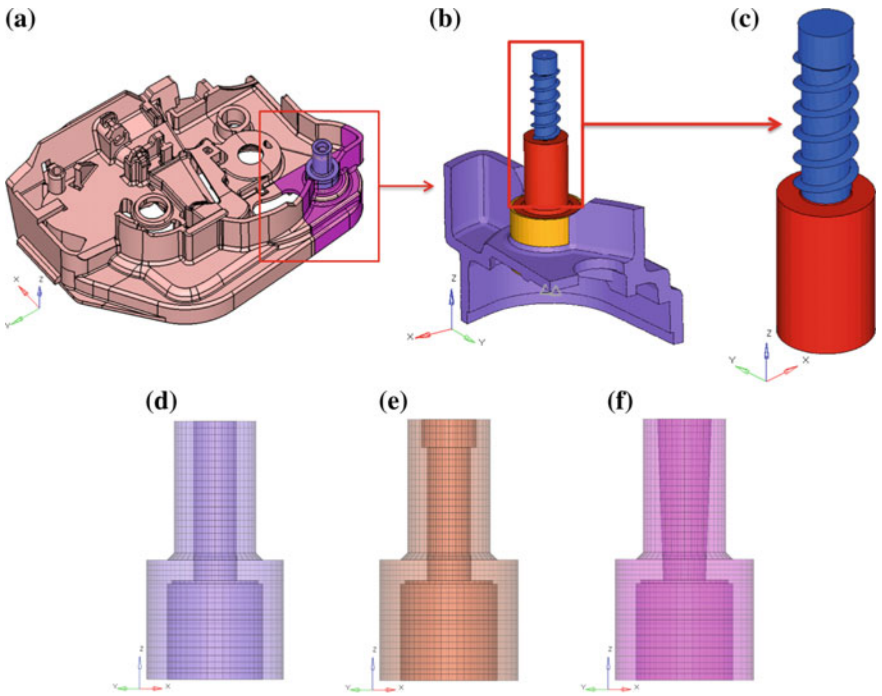
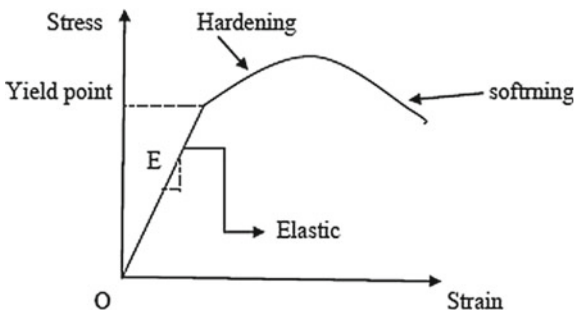


Fig. 6.3 **a** Component considered **b** Simplification of geometry **c** Region of interest: Screw post **d** Design 1 **e** Design 2 **f** Design 3

Fig. 6.4 Strain hardening behavior



6.3.2 *Eulerian Domain*

Here, our region of interest, the screw post, is modeled using Eulerian formulation. Unlike Lagrangian elements, the Eulerian elements are not completely filled with material. Instead, each Eulerian element has a particular volume fraction value associated with it, indicating how much volume of the element is full of material. Usually, the Eulerian mesh is made larger than the actual geometry. This is done so that the material inside the Eulerian mesh has adequate space available to flow.

[4] The Eulerian mesh, when created, by default, is empty, i.e., without any material. The material distribution needs to be defined in the Eulerian mesh in the initial step of the simulation, by calculating the volume fraction of this mesh with respect to a reference Lagrangian mesh. Reference Lagrangian mesh represents the actual geometry. This volume fraction is called Eulerian volume fraction (EVF). An element can take all the values from completely filled (EVF = 1.0) to completely empty (EVF = 0.0). Eulerian elements are capable of containing multiple materials at the same time. The sum of volume fractions of all these materials (including void material) equals one.

[5] The time incrementation algorithm is based on an operator split of the governing equations. This results in Lagrangian phase, followed by the Eulerian phase. This formulation is called "Lagrange-plus-remap." During the Lagrangian phase, the nodes are assumed to be temporarily fixed to the material and material and elements deform together. During the Eulerian phase, deformation is suspended; the elements experiencing large deformation are automatically remeshed, and the material flow between neighboring elements is calculated.

6.3.3 Eulerian–Lagrangian Contact Model

The rigid screw is discretized using elements with the Lagrangian formulation. The Lagrangian object can move through the Eulerian mesh until it encounters any material. Then, the contact algorithm starts to act.

[6] The Eulerian–Lagrangian contact formulation used in this work is based on an enhanced immersed boundary method. It is called general surface-to-surface contact. Here, the Lagrangian object is placed in the void region of the Eulerian mesh. The contact algorithm automatically calculates and tracks the contact interface between the Eulerian and Lagrangian domains. This contact method also does not require conforming mesh in the Eulerian region. It is observed that, often, a regular grid of Eulerian elements gives good accuracy.

[7] The surface-to-surface contact formulation enforces the contact conditions as average over nearby slave nodes. This differs from node-to-surface contact as that enforces the contact conditions only on individual nodes. The averaged regions are approximately centered on the slave nodes but also consider adjacent slave nodes. This may lead to small penetrations of the master surface into slave surface, but it also allows the forces to spread out over multiple slave nodes. The spread of the forces leads to a smoothing effect, i.e., for a given mesh refinement in master and slave surfaces the stresses observed are more accurate.

Table 6.1 shows the element types considered for the simulation.

Table 6.1 Element types used in the simulation

Component	Formulation	Element type	No. of elements
Self-tapping screw	Lagrangian	R3D3 and R3D4 (Tria and Quad)	1109
Screw post	Eulerian	EC3D8R (Hex)	30,000
Screw post (reference)	Lagrangian	C3D8 (Hex)	4800

6.3.4 Boundary and Loading Conditions

Symmetry boundary conditions are applied on the bottom surface of the post. The screw is given translational and rotational displacements along the axis of the screw post. The values for the displacements are calculated based on the design of the screw thread.

6.4 Results and Discussions

The threads can be visualized using a special output variable specific only to Eulerian regions, called EVF—Void (Eulerian Volume Fraction—Void). This variable shows the value of the volume fraction of the Eulerian elements with respect to the void. Hence, the value of EVF—Void = 1 signifies the presence of a complete void, i.e., no material filled in the elements. Here, the value of 0.5 is observed to provide the best visualization of the tapped threads.

Three unique designs are chosen, and identical boundary and loading conditions are applied to all. Based on the design, the number of threads engaged during fastening is different and the same can be noticed in Table 6.2.

Here, it is observed that the Design 1 and Design 2 have the highest number of engaged threads. However, since the hole available for self-tapping itself is tapered, in Design 2, the initial threads may not be able to provide adequate holding strength. This can be seen from the formed threads after the simulation below (Fig. 6.5).

Further, the reaction moment (output variable: RM) for the self-tapping process is obtained from the simulation as an output. The complete simulation for each design

Table 6.2 Number of threads engaged

Design	No. of threads engaged
Design 1	5.47
Design 2	4.32
Design 3	5.47

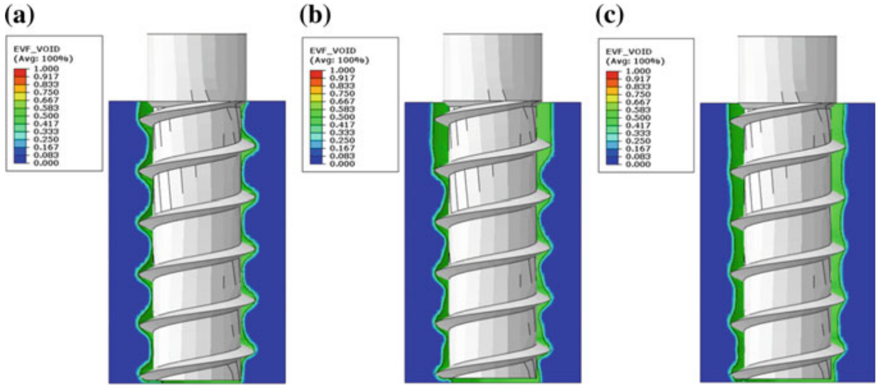


Fig. 6.5 **a** Design 1 **b** Design 2 **c** Design 3

Table 6.3 Maximum moment during a step

Design	Self-tapping process (step 1) (N-m)	Unscrewing process (step 2) (N-m)	Retightening process (step 3) (N-m)
Design 1	0.90	0.62	0.73
Design 2	0.86	0.76	0.61
Design 3	0.99	0.78	0.55

takes place in three steps. The first step deals with the actual self-tapping process, and the maximum moment required by the process is calculated. The second step involves unscrewing of the screw, and the third step calculates the moment required to retighten the screw into the tapped hole. Table 6.3 provides the values for the maximum moments in each of the above-mentioned steps for all three designs.

It is evident that the moment required to fasten the screw is high for the very first time and then reduces for the next steps. This is because, the first time, the material is formed into the shape of the threads by the screw. In the later steps, the screw just retraces its path through the screw post.

6.5 Conclusion

The current work presents the methodology for simulating a self-tapping process using the CEL approach. This approach, though computationally expensive, yields acceptable results for evaluation of torque required for self-tapping and clear visualization of the threads. This methodology may be used to evaluate different designs for self-tapping and tightening torques with sufficient accuracy.

References

1. Aryal, A.: A coupled Eularian-Lagrangian extended finite element formulation for moving interface problems and damage transport in hyperelastic media. Graduate School of Vanderbilt University (2014)
2. Duobu, F.: The CEL method as an alternative to the current modelling approaches for Ti6Al4 V orthogonal cutting simulation. Proc. CIRP **58**, 245–250 (2017)
3. Roy, R.G.: Elasto-plastic analysis of plate using ABAQUS. National Institute of Rourkela (2015)
4. Abaqus Analysis User's Guide, Section: 14.1.1 Eulerian Analysis, Material Interfaces
5. Abaqus Analysis User's Guide, Section: 14.1.1 Eulerian Analysis, Eulerian Volume Fraction
6. Abaqus Analysis User's Guide, Section: 14.1.1 Eulerian Analysis, Interactions, Formulation of Eulerian-Lagrangian contact
7. Abaqus Analysis User's Guide, Section: 38.1.1 Contact formulations in Abaqus/Standard, Discretization of contact pair surfaces