3D Finite Element Modeling of an Assembly Process With Thread Forming Screw

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1 Introduction

Thread forming screws are one of the most frequently used assembly procedures in the automotive industry. Self tapping screws are also commonly used for assemblies made of materials, which transmit minimal exterior loadings, such as wood or thermoplastic materials. Thread forming screws are suitable for highly ductile metallic materials, which consequently transmit high loadings. They are designed to perform direct assembly by a thread forming process in the lower part of the assembly to avoid the finishing operations that are necessary with traditional screws. Moreover, the chip evacuation problems, which are encountered with self tapping screws, can be avoided.

However, until recently, few studies related to auto forming screws have been presented in part due to the fact that no dimensional specifications exist for these kinds of screws except for ISO 7085 [1]. In fact, most of the existing published works concerning form tapping are based on experimental studies and on mechanical models for load calculation during the finishing processes. Hayama [2] analyzed autoforcing screws and established a mechanical model using the minimal energy method and a theory based on the study of a partially plastically deformed thick cylinder. Simultaneously Henderer and Von Turkovich [3,4] developed an approximation model by considering the tapping process as an indentation problem, whereas Chowdhary et al. [5,6], in a later study, took into consideration the elastic reversal process for calculating the tapping forces. It should be noted that the applicability of the results from these studies is limited to their experimental tests, since several coefficients were obtained by reverse identification from the experiment.

Seneviratne et al. [7,8] investigated an assembly made up of plates of vulnerable materials using M4 and M6 thread forming screws to monitor the tightening torque in an automated assembly chain. This study was carried out considering that the ideal screw insertion process can be discretized into three main phases: screw engagement, screw advancement, and tightening. For each phase, a model based on a quasistatic analysis was set up to establish the respective tightening torque, screw engagement torque, and screw advancement torque, which can be further decomposed into thread forming and friction resistance components. Two experimental samples, one made of ABS plates and the other of polycarbonate, with circular core screws and triangular cross section threads were used to validate the model.

Fromentin [9] conducted experimental investigations on tapping based on the deformation of different materials and notably high strength steels. In this study, the material flow during the deformation process and the shape and mechanical characteristics of the threads were inspected.

Recently, Warington et al. [10] used an indentation process based on an experimental study on tapping to study the shape of the hole at the crest of the threads.

It is worth nothing that the finite element (FE) simulations made so far tend to be indentation [11,12], forming, forging, or extrusion simulations. Martin [13,14] developed 3D FE modeling of the rolling process on a plate of ACME screws using MSC software. In this same framework, Domblesky and Feng [15,16] built 2D and 3D models for thread rolling screw under “DEFORM 3D,” whereas Pater et al. [17] used “SUPER FORGE 2000” to model a new rolling process. Finally, Warrington et al. [18] established FE models under DEFORM 3D software to improve tap design in form tapping and to highlight the hole phenomenon at the crest of the thread by considering form tapping to be equivalent to linear scratch experiment.

A review of the literature has revealed that no FE simulations appear to have been published for thread forming screw assemblies. Consequently, the intent in the current work was to develop a 3D model of such assemblies. The main objective was to determine displacements during the forming process and the shape of the threads and to establish the screwing or torque function based on different parameters such as screw rotation speed and the diameter of the lead hole.

2 Modeling of the Assembly Procedure

In recent years, FE simulation codes have developed considerably with advances in the computer hardware technology and numerical resolution methods. Consequently, numerical models for simulating certain processes, such as rolling, forging, or hydro-forming, have become commonplace because they are accurate.
and, moreover, reduce the computational time. The numerical simulation of the thread forming assembly process presented in this paper was conducted using ABAQUS 6.5.4 FE software [19]. ABAQUS is a powerful FE code built on finite elements method and is suitable for a range of simulations from relatively simple linear problems to complex nonlinear ones. The simulations presented in this paper were conducted using the Explicit solver of ABAQUS 6.5.4, which had proved to be efficient for solving 3D quasistatic problems with very complex contact conditions and very large deformations such as are encountered in the thread forming process.

General geometry of the thread forming screws. Since no prescriptive dimensional guidelines have been developed for thread forming screws, their geometry and the assembly mountings often differ from one manufacturer to another. Nevertheless, this study considers only screws with ISO threads, as shown in Fig. 1, because in the automotive industry, defective thread forming screws are replaced with standard ISO screws.

The cross section A-A of a thread forming screw (Fig. 1) may be either circular or trilobed. Moreover, the screw can be subdivided into two distinct areas: a tightening zone and a thread forming zone. The latter, usually made up of three to five threads, has a linear profile allowing progressive penetration in the subassembly during the tapping phase, whereas the tightening zone is similar to a standard ISO screw.

Loading and simulation parameters. The model used in the study was composed of three principal elements, as shown in Fig. 2: a thread forming screw with a circular cross section M10 × 12, a lower 4 mm plate (plate 1) in which the screw tapped its threads, and a 1 mm plate (plate 2) mounted 0.5 mm above plate 1 to simulate the preloading phase and to set the preload for several types of assemblies and different tightening torques. This will be presented in a further paper. The two plates were both modeled as AISI 1018 steel, which is commonly used in the mass production of these assemblies. However, as a 360 deg model would have required an estimated calculation time of around one month, a 45 deg sector, representing 1/8 of the joint was modeled to maintain a good compromise between calculation time and an accurate representation of thread forming.

The contact surfaces of the thread forming screw were case hardened to obtain a screw hardness greater than the hardness of the deformed plate. In addition to this, deformation in the subassembly was only described along the two plates. Under these conditions, the screw could be modeled as a rigid body without disregarding the real behavior of the assembly during the assembly process. Consequently, the CPU calculation time was reduced, since the displacement of the screw, considered as a discrete rigid body, was guided by a unique reference point, as shown in Fig. 2.

However, the two main concerns of this study were the step by step displacement of the plate surfaces during the tapping phase and the variation in the tapping torque via the lead hole diameter and the rotational speed of the screw. Note that the tapping torque, also called torque required to advance the screw, incorporates the thread forming torque and the friction torque.

The following cases and assembly parameters were investigated (Table 1).

It is computationally impractical under ABAQUS to model quasistatic events such as the metal forming process in its natural time period. Literally millions of time increments would be required. Thus, it was necessary to increase the speed of the process for an economical solution. There are two possible approaches: the time scale of the process can be artificially reduced by increasing the loading rate or the stable time increment can be increased by using a mass scaling factor. In this paper, the latter is used.

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**Table 1 Finite element models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Lead hole diameter (mm)</th>
<th>Operating rotation speed N of the screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1.1</td>
<td>9.16</td>
<td>N=200 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 1.2</td>
<td>9.26</td>
<td>N=200 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 1.3</td>
<td>9.48</td>
<td>N=200 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 1.4</td>
<td>9.6</td>
<td>N=200 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 2.1</td>
<td>9.48</td>
<td>N=200 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 2.2</td>
<td>9.48</td>
<td>N=300 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 2.3</td>
<td>9.48</td>
<td>N=400 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 2.4</td>
<td>9.48</td>
<td>N=500 rpm, 1 pitch per revolution</td>
</tr>
<tr>
<td>Model 2.5</td>
<td>9.48</td>
<td>N=600 rpm, 1 pitch per revolution</td>
</tr>
</tbody>
</table>

**Fig. 2** Geometrical parameters used in the modeling

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Transactions of the ASME
behavior law

\[
\sigma_t(e, \dot{e}, T) = (A + B\dot{e}^n) \left(1 + C \ln \frac{\dot{e}}{\dot{e}_0}\right) \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right)
\]

where \(A, B, n, C, \dot{e}_0\) are all model parameters, \(T_m\) is the material melting temperature, and \(T_r\) is room temperature. The model parameters corresponding to the mechanical behavior of 1018 steel [18], which was used in the screwing experiments, are shown in Table 2.

### Table 2 Coefficients of the Johnson–Cook constitutive model [10]

<table>
<thead>
<tr>
<th>(A) (MPa)</th>
<th>(B) (MPa)</th>
<th>(n)</th>
<th>(C) (s(^{-1}))</th>
<th>(T_r) (K)</th>
<th>(T_m) (K)</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>560</td>
<td>300</td>
<td>0.32</td>
<td>0.022</td>
<td>1</td>
<td>298</td>
<td>1773</td>
</tr>
</tbody>
</table>

First, in order to represent the material behavior of 1018 steel over such a large range of strain-rates, slight modifications were made to the original Johnson–Cook material constitutive model using the studies of Vural et al. [21]. Vural et al. modified the Johnson–Cook constant \(C\) and \(\dot{e}_0\) so that they are dependent on the strain-rate.

Second, thermal phenomena were not taken into consideration in the models, and isothermal behavior was used to simulate the thread forming. As the screw was modeled by a rigid body, the heat generated during the forming process could not be diffused through the screw but only by the deformed plate. Kapoor and Nemat-Nasser [22] made experimental investigations of the amount of heat generated during high strain-rate plastic deformation in 1018 steel. The heat generated is either lost to the surroundings or causes localized heating in the workpiece. The increase in temperature, in turn, lowers the flow stress in the material. This is known as thermal softening. The use of isothermal material data in the numerical simulations assumes that no heat is generated and may overpredict the flow stress by ignoring the thermal softening effect. So, a coefficient was calculated from the experimental results to correct the screwing torque value obtained from the numerical simulation and the isothermal material constitutive data.

In order to be closer to reality, as the thread forming process is very fast, FE models could be improved by using the new coefficients proposed by Vural et al. and by employing adiabatic material data.

### Boundary conditions

As mentioned previously, the displacements of the screw nodes were monitored using a single reference point, since the screw was modeled as a rigid body. Thus, the screw motion was in advance by 1 pitch per revolution for a rotation speed between 200 rpm and 600 rpm at the reference node. During each simulation, the displacements of the lower
plate's nodes were restricted on the free external surface (Fig. 4). A symmetry condition was applied on the face where the forming process occurred, whereas the displacement of all the remaining faces was left free to visualize the 3D material flux. Moreover, only translation along the screw axis was allowed at the upper plate of the assembly.

However, the relevance of the boundary conditions at the lower subassembly is open to discussion. First, during the real tightening process, plate 1 lies on its lower face and is fastened on its upper face. In the model, a clamping condition is defined. This is justified by the fact that it does not affect the subassembly behavior during the thread forming process, since enough material is kept radially. Furthermore, in the case of thick plates, radial extension (often) is negligible, and thus thread forming occurs only by material displacement. Moreover, as a result of the clamping condition, material flows along the Z direction, which is the case in the real world. The symmetry condition is so restrictive that no material flow is possible radially, which is contrary to the real situation, since material can flow radially with the helicoidal motion of the screw. However, the symmetry condition is better than a free edge condition. This fact has been highlighted by numerical simulations. In this framework, radial material flow with a free edge condition is opposite to the rotation of the screw, which is physically impossible. Finally, a free edge condition is defined at the face where the screw crosses the subassembly in the radial direction. In a first approach, a symmetry condition was defined. Consequently, the material radial flow was prevented, and calculation convergence failed due to the excess of material not evacuated radially. Thus, the free edge condition was chosen. However, it should be noted that, with this condition, the radial material flow is too large. To counter the influence of the boundary conditions defined above, two portions of 11.25 deg were subtracted from the surrounding of the boundary conditions area. Thus, the angular sector of 45 deg was cut into a 22.5 deg sector during the postprocessing phase. Under these conditions, the effects of the boundary conditions were altered since results were investigated away from the boundary condition areas.

Finally, contact conditions at the interface between the screw and the lower plate were modeled using the ABAQUS “contact pair” option, based on a Coulomb model with an arbitrary coefficient of friction equal to 0.1. This friction coefficient of 0.1 corresponds to the average theoretical coefficient measured on the manufacturer’s M10 thread forming screws. The models presented in this study were subsequently experimentally tuned to identify the coefficient of friction for each plate/thread forming screw configuration.

3 Modeling of the Assembly Procedure

ABAQUS simulations were carried out using a PC biprocessor AMD opteron 252–2.6 GHz equipped with 4 GB DDR 400 MHz ram. CPU calculation times ranged between 32 h and 107 h depending on the conditions simulated. Note that only the forming with screw insertion process was simulated. Simulation was stopped as soon as the head of the screw was determined to be within 0.1 mm of the contact zone of the upper plate.

Results comparison. The thread forming process using a thread forming screw is somewhat similar to a form tapping operation. Since the only available research on micrographic works concern tapping-deformation process, the FE results were compared with experimental results obtained from these studies. Figure 5 shows micrographs obtained from a tapping-deformation process carried out through an M12 machinery tap (Protodyn M12×1.5). These micrographs were taken from the Fromentin’s experimental study [9], which is one of the few papers studying the step by step thread forming process. The results of this experiment and the results of the FE simulation (model 1.1) are compared qualitatively. Figure 5 retraces the forming of the thread section from the simulation results. At first glance, the experimental and FE results appear to be in good agreement. In order to further validate these results, an experimental study will be conducted using the same conditions and the same material.

At step 1, the thread forming screw initially contacts the material and thus starts progressively forming the right flank of the thread, which reaches its final shape at step 8. At step 5, the screw would have achieved a complete first rotation, and the thread forming screw would have started forming the left flank simultaneously with the right flank. At step 12, the thread forming is completed.

It should be noted that screwing the screw induces thread formation by material displacement. Subsequently, a hollow shape can be seen at the peak of the thread due to the material flow. This particular shape is similar to the form observed in the experimental study.

Moreover, the bottom of the thread is rounded. One cannot generalize and assume that this rounded shape is an intrinsic characteristic of the thread since the shape of the bottom is directly related to the geometry of the thread forming screw. Also note than the lead hole diameter $D_0$ (Fig. 6) is not materialized on the whole thread, since it corresponds to the middle line between the peak and the bottom of this thread.

Under the effect of the thread forming screw, material flows from areas located at diameters greater than the hole diameter to areas located at smaller diameters. Thus, it can be concluded that the material flow is inversely proportional to the lead hole diameter and, consequently, the final geometry of the thread and the height of the hollow peaks differ considerably. This fact highlights the high dependence between the thread and the lead hole diam-
eter, which will further analyzed. Finally, the five experimentally identified zones related to the material flux can be also studied in FE simulations (Fig. 7).

From the displacement plot and the meshing shape, it can be seen that the material at the core of zone 1 (Z1) did not undergo any deformation, which is expected. Zone 2 (Z2), where the head of the screws acts directly, is strongly deformed. In zone 3 (Z3), material flows along the tap flanks. The core of the thread, identified as zone 4 (Z4), is slightly deformed. Finally, zone 5 (Z5), which represents material on the free edge, undergoes the greatest deformation.

Fig. 6 Hole diameter before and after thread forming

Fig. 7 Comparison of the radial displacement of material during the thread forming process between the experimental study [9] and FE simulations
displacements. However, one can note that the core of this zone is observed to be only slightly deformed, while the material basically flows from the thread flanks.

Energy balance. It is possible, in ABAQUS Explicit, to monitor the calculation increment, the maximal values of the outputs, and the energy balance. In this framework, it is necessary to check the energy conservation at every step of the simulation to validate the numerical model. The energy equilibrium is given in ABAQUS by Eq. (2)

\[ E_i + E_{VD} + E_{FD} + E_{KE} - E_W = E_{TOT} = \text{constant} \]  

where \( E_i \) is the internal energy (elastic, inelastic and hourglass energy), \( E_{VD} \) is the energy absorbed by viscous dissipation, \( E_{FD} \) is the frictional dissipation energy, \( E_{KE} \) is the kinetic energy, \( E_W \) is the energy linked to the work of external forces, and \( E_{TOT} \) is the total energy in the FE model.

The different energies presented in this model are the energies in the overall model. In this study, they are relative to the lower plate since the screw is considered to be rigid. Besides, it is impossible to simulate the forming process on the real time scale since millions of increments and thousands of calculation hours would be necessary due to the size of the meshing elements. Thus, forming simulations were conducted considering a quasistatic problem, and consequently CPU calculation time was improved by reducing the increment time to around \( 10^{-6} \) s. This value is optimal for this study, since it prevents discontinuities between the elements. Note that the increment time is reduced under ABAQUS by using the “mass scaling” option.

From Fig. 8, which represents the different energy functions over time, it can be observed that the energy equilibrium is approximately conserved. The figure also points out the fact that the frictional dissipation energy is preponderant in comparison with the viscous energy dissipated. On all the models presented in this paper, the frictional dissipation energy always represents about 90% of the energy linked to the work of external forces, where the friction coefficient \( f \) equals 0.1.

It is necessary to monitor the ratio of kinetic energy/external energy, which should not exceed 1–5% if the simulation is to remain in the conditions of a quasistatic process. Moreover, the ratio of hourglass energy/external energy should not exceed 10%, where hourglass energy is the energy loss in the model. It is introduced during calculation to monitor the numerical parasite distortion modes principally induced by double integration elements such as C3D8R elements. As shown in Fig. 9, the above conditions were respected in this study.

ABAQUS gives the energy balance at each predefined time interval of the simulation. Looking at the results of this energy balance, the screw forming torque can be calculated for each increment using Eq. (3). This method was inspired from the calculation of the outflow rate for hydraulic pumps [23].

\[ C_{ti} = \frac{E_{W_{i+1}} - E_{W_i}}{t_{i+1} - t_i} \times \frac{1}{N} \]  

where \( C_{ti} \) is the instantaneous screwing torque calculated at time \( i \) in the simulation, \( N \) is the rotation speed in radians per second, \( E_{W_{i+1}} \) and \( E_{W_i} \) are the energy linked to the work of external forces at the time \( i+1 \) and \( i \), \( t_{i+1} \) and \( t_i \) are the time values in seconds. For example, the results of the screwing torque are plotted versus time for model 2.3. However, the numerical models presented in this paper correspond to 45 deg angular sectors of the assembly. The screwing torque of the whole plate is obtained by adding the screwing torques of each sector. Moreover, the curves have to be shifted at time intervals of \( \Delta t \) corresponding to the angular shifts of the sectors (Fig. 10).

Figure 11 illustrates this method, which is represented in the results for model 2.3. Note that using a screw with a trilobular rather than a circular shape reduces the contact areas during the thread forming process, and thus the screwing torque.

Influence of the lead hole diameter. Under the action of the device, material flows from the zones with a diameter greater than the lead hole diameter to areas with smaller diameters, as shown in Fig. 6. Subsequently, the lead hole diameter considerably affects the shape of the threads and, therefore, the thread forming torque. Figure 12 shows the evolution of the tightening torque as a function of time and the final thread shape for models 1.1–1.4.

It is possible to observe with the aid of Fig. 6 that the two sectors which have a larger diameter than the lead hole diameter remain deformed. This effect is visible at the time the screwing is ceased and in the overall model. In this study, they are relative to the lower plate since the screw is considered to be rigid. Besides, it is impossible to simulate the forming process on the real time scale since millions of increments and thousands of calculation hours would be necessary due to the size of the meshing elements. Thus, forming simulations were conducted considering a quasistatic problem, and consequently CPU calculation time was improved by reducing the increment time to around \( 10^{-6} \) s. This value is optimal for this study, since it prevents discontinuities between the elements. Note that the increment time is reduced under ABAQUS by using the “mass scaling” option.

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As shown in Fig. 12, the lead hole diameter has a direct impact on the maximum tightening torque. Thus forming a thread from a hole diameter of 9.15 mm instead of 9.6 mm induces a 2.5 times greater torque (11 N m for 9.6 mm and 28 N m for 9.15 mm with a friction coefficient of 0.1). Eight other simulations were run in order to confirm the impact of the lead hole diameter with two other friction coefficients. On these models, thread formation in a 9.15 mm lead hole diameter led to a maximum screwing torque multiplied by 2.5. These simulations show the importance of the friction coefficient in screw forming: The energy dissipated by friction always represented about 90% of the energy linked to the work of external forces in all the simulations. Consequently, the designer must compromise between a minimal and a maximal lead hole diameter in order to supply mechanical resistance for load transmission and limit the torque to advance the screw respectively.

Influence of the operating rotation speed. When optimizing the process in an assembly chain, the influence of the operating rotation speed on the screwing torque should be investigated. In fact, an increase of this speed considerably decreases the cycle duration. Thus, a 9.48 lead hole diameter was chosen for this study, as it corresponds to the process value. Besides, if the effect of this parameter is negligible, the CPU calculation times can be considerably reduced. For this purpose, the models 2.1–2.5 were investigated. Figure 13 features the variation in the screwing torque with time together with the final shape of the threads. Note that the advance is fixed to 1 pitch per revolution, and thus the displacement velocity of the screw must be monitored.

The increase in the rotational speed of the screw comes along with an ascending time on the time/forming torque curves. However, the results also suggest that this speed has little impact on the screwing torque/insertion depth curve. Moreover, the final...

Fig. 11 Transition between the curves of the tightening torque relative to 45 deg sector to the curve and relative to the complete plate

Fig. 12 Influence of the hole diameter on the tightening torque and the final thread shape

Fig. 13 Influence of the rotation speed of the screw on the tightening torque, the final thread shape, and the CPU time
shape of the threads remains intact. This small influence of the rotational speed is explained by the importance of the energy dissipated by friction, which always represents about 90% of the energy related to the work of external forces in the energy balance in all simulations. Moreover, 1018 steel is not highly dependent on strain rate. Thus, the slight influence of the rotational speed might be case-specific. The differences between the various models for the ratios of kinetic energy/internal energy and hourglass energy/internal energy are advantageous for monitoring these ratios. Model 2.5 ($N=600$ rpm) presents the most favorable energy balance with a kinetic energy/internal energy ratio lower than 1% and an hourglass energy/internal energy ratio of less than 4%. The ratio of kinetic energy/internal energy was also very accurate for models 2.1, 2.2, 2.3, and 2.4, whereas the hourglass/internal ratio was less successful with a value of around 11% for model 2.1, as shown in Fig. 14.

4 Conclusion and Perspectives

This paper presents a simulation study of the material flux and, more particularly, the step by step displacements during the assembling procedure of a thread forming process. A parametric study with a friction coefficient of 0.1 showed the important impact of the lead hole diameter on the thread screwing torque, whereas the effect of the screw operating rotation screw was relatively small. Consequently, it would be interesting to set a minimal hole diameter during the design phase to provide sufficient mechanical resistance of the threads along with minimal screwing torque. The study shows that the screw rotational speed has negligible influence on the maximum screwing torque. This result is probably the consequence of the material behavior law hypothesis. This material behavior could be refined even though the ratio between the screw forming energy and the frictional energy is low.

In the aim of developing a robust industrial dimensioning tool, this model can be extended for other types of assemblies and also for establishing the preload. In this framework, the operating rotation speed of the screw (600 rpm) in model 2.5, which is the most economical in terms of CPU time, presents the most favorable energy balance. Therefore, it will be used in future FE models. An experimental campaign is also planned for validation and adjustment.

References