Comparison between implicit and explicit FE models for simulation of hot rod rolling

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Abstract

The objective of this paper is to compare implicit and explicit FE approaches for the simulation of the hot rod rolling process. This research has been focused especially on the evaluation of bar geometrical features after rolling.

Different FEM codes have been used: implicit time integration by MARC Autoforge and explicit time integration code by LS-DYNA.

Particular attention has been paid to the prediction of bar spread, cross sectional profile and area contraction ratio.

Numerical results have been compared against experimental data to discuss the applicability, the accuracy and the efficiency of these approaches for hot rolling process simulation by numerical techniques.

Keywords: hot rolling, FEM analysis, efficiency, implicit and explicit simulation.

1 Introduction

Hot rod rolling involves complicated process features such as high temperature, high speeds and high deformations; furthermore, due to the high speed of the bar, it is impossible to control and modify the process parameters during the process is working. Hence, the design phase is very delicate; an inappropriate design of process parameters: temperature, rolls speeds, rolls groove geometries, could involve roll groove overflowing or incomplete fulfilling of material, roll overloading and/or permanent damages, product defects and/or residual stress needing to stop the production and absolutely redesign the entire process.

For long time, hot rolling sequences were designed starting by empirical knowledge of this process and formulae never checked against empirical data; succes-
sively, the increasing of productivity and process efficiency, requested by the market, made necessary a better understanding of the hot rolling process.

Great progresses have been made since the beginning applications of FE models in hot rolling [1, 2, 3, 4, 5, 6]; hardware and software (especially by the introduction of explicit time integration codes) improvements have been developed with drastic reduction of the calculation time and higher accuracy of the new models; consequently, numerical models become an useful tool for rod rolling design.

The main advantage of explicit FE codes consists on less memory requirements, moreover they are more efficient since the employment of dumped masses (the stiffness matrix is diagonal and consequently low efforts are needed for its inverse matrix calculation).

Furthermore, the employment of same tricks in explicit approach let to reduce the calculation time: increasing of process velocities and mass scaling to reduce the critical time step. Anyway, this artificial inertia could decrease the accuracy of the solution.

The present investigation is a development of a previous work [7] in which the width of a rolled rebar was analyzed. The experimental data and the analytical and numerical models (by implicit codes) were compared for two rolling passes (round–oval and round–flat oval). In this work, spread, radius of curvature and cross section area after rolling have been focused in order to define all geometrical features of the rolled rebar.

Numerical results have been reported with the models features: number of elements, element distortion ratio and element size, successively; the calculation time of all the simulations has been compared to estimate their efficiency, and finally, the error in the evaluation of final width and radius of curvature have been analyses to estimate their accuracy.

The comparison of experimental data with FEM models by implicit and explicit approach results shows their efficiency and consistency for the prediction of the geometrical features for both the analyzed passes.

2 Implicit and explicit features

Rod rolling involves complicated deformation process with material, geometrical and contact non–lineairities.

The introduction of explicit time integration codes has permitted to develop even more accurate models with high performances and accuracy. The main difference between the implicit ad explicit approach consist in the way to solve the basic differential equation eqn (1).

$$M\ddot{U} + C\dot{U} + KU = R$$  \hspace{1cm} (1)

By implicit time integration, the equation of equilibrium (1) is solved at time \(t + \Delta t\). On the other hand, the equilibrium is considered at time \(t\) in order to calculate the displacements at time \(t + \Delta t\). All effects of damping matrix \(C\) are
neglected and the eqn (1) become the following eqn (2):

\[ \mathbf{M}^t \ddot{\mathbf{U}} = \mathbf{R}^t - \mathbf{F}^t \] (2)

where \( \mathbf{F}^t \) is the nodal point force. Even though implicit simulation involves several reiteration for each time step while using explicit approach the solution simply corresponds to a foreword marching in time [8], the shortcoming in the use of the central difference method (used in many explicit codes) lies in the severe time step restriction: for the stability of the simulation, the time step \( \Delta t \) must be smaller than a critical time step \( \Delta t_{cr} \) which is given by the following formula:

\[ \Delta t_{cr} = \frac{T_n}{\pi} \]

where \( T_n \) is the smallest period in the finite element model.

As above mentioned, mass scaling is often used to increase the \( \Delta t_{cr} \) (reducing the number of steps needed to cover the entire simulation time). Moreover, speeding up the process let to reduce the total time of simulation with a further reduction of CPU time.

![Figure 1: Evaluation of geometrical features of the cross section of the rolled rebar models.](image)

(a) Spread evaluation  (b) Curvature evaluation

If the mass scaling and process speed up is too high, the analysis accuracy could be reduced drastically due to contact problems, nonphysical deformations and unreal inertial phenomena.

A good compromise between model efficiency and accuracy might, instead, reduce simulation time (in comparison with implicit based models) without decreasing its reliability too much.

### 3 FE models

Numerical models (implicit, using MARC Autoforge and explicit using LS–DYNA [9]) are based on the same mathematical model. A wide set of models
(two implicit and five explicit whose features are reported in table 1) have been
developed for the both passes analysis to study and compare their accuracy, effi-
ciency and convergence of the solution. In all the models the process has been
considered to be isothermal at 1200(°C); the bar and rolls materials behaviors
have been assumed to be respectively elastoplastic and rigid. A symmetry plane
has been used for a further reduction of the simulation run–time; moreover, a rigid
plane, with a prescribed velocity, put the bar in contact with the roll. The elements
used for bar discretization have been 8–node bricks while the roll has been mod-
eled by 4–nodes shells (with one integration point). The contacts has been evalu-
ated using a Coulomb coefficient between rolls and bar by the following formula:

\[ F = (1.05 - 0.0005T) \cdot K_1 \]

\( K_1 \) must be evaluated to determine the friction coefficient. The value of this coeffi-
cient has been 0.75 for the round oval pass and 0.8 for the round flat oval [10].
Thus, the values of the friction coefficient were, respectively, 0.33 and 0.34 for the
two passes.

Figure 2: Workpiece and rolls in FE models after rolling.
Table 1: Models features.

<table>
<thead>
<tr>
<th>Model</th>
<th>NOE</th>
<th>Cross section length (mm)</th>
<th>Axial length (mm)</th>
<th>Distortion ratio</th>
<th>CPU Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oval</td>
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<tr>
<td>implicit 1</td>
<td>260</td>
<td>3.80</td>
<td>10.0</td>
<td>2.63</td>
<td>1325</td>
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<td>implicit 2</td>
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<tr>
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<td>298</td>
</tr>
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<td>explicit 3</td>
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<td>3.4</td>
<td>1.00</td>
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<td>1.03</td>
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<tr>
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<td>2.0</td>
<td>1.18</td>
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<tr>
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<td>7335</td>
<td>1.70</td>
<td>1.8</td>
<td>1.05</td>
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<td>Flat Oval</td>
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<tr>
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<td>1.00</td>
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</table>

Note: NOE is the acronym for number of elements. It represent the number of elements used for the rebar discretization.
The distortion ratio is the ratio between the general axial length and the cross section length.

Due to the limited number of elements in which the workpiece could be discretized with Autoforge (LS-DYNA doesn’t have any limitation on the number of elements), implicit and explicit models have been featured by different meshes (fig. 2).
To avoid the edge effects, FEM spread and radius evaluation has been conducted by considering the bar’s outer nodes in the middle section (fig. 1).
Figure 3: Convergency plots. These plots show the measured values of the width by all models for both passes.

Figure 4: Total calculation CPU time (on a P4 2.6 GHz).

4 Conclusions

The comparison among numerical models results (shown in fig. 3) turns out both implicit and explicit approaches (reported in table 2) to provide good evaluations for spread (the error against experimental data ranges from 0.35–2.4% as shown in fig. 5).

On the other hand, the radius of curvature is not properly evaluable by implicit models (the error against experimental data goes up to 175% ) while, when explicit models are employed, good evaluations even on the curvature are provided (the error is less than the 2% as shown in fig. 6). Obviously, this difference on curvature is due to the lower number of section elements (thus bigger elements dimen-
Figure 5: Numerical models error in the evaluation of final spread.

Figure 6: Numerical models error in the evaluation of final curvature.

Table 2: Numerical results.

<table>
<thead>
<tr>
<th></th>
<th>Maximum spread (mm)</th>
<th>Radius of curvature (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Imp. Model</td>
<td>Exp. Model</td>
</tr>
<tr>
<td>Round–Oval</td>
<td>35.19</td>
<td>35.70</td>
</tr>
<tr>
<td>Round–Flat Oval</td>
<td>44.30</td>
<td>43.68</td>
</tr>
</tbody>
</table>

Note: Numerical results are referred to the highest accuracy model for both implicit and explicit set of simulations.

It is noticeable how much the workpiece’s size is important: while big rods have to be rolled, bigger elements could be employed for discretization, hence, the advantage of explicit against implicit approach further increases (because of the critical time step dependency on elements dimensions).
Explicit models let save much CPU time compared with implicit ones as shown in fig. 4 (up to 18 times in round–flat oval pass and up to 2 times for round–oval pass).

References