Effects of Increasing Mass Scaling in 3D Explicit Finite Element Analysis on the Wire Drawing Process

Jabbar Gattmah\(^1,3\), Suha K. Shihab\(^1\), Muzher Taha Mohamed\(^1\) and Ali Laftah Abbas\(^2\)

\(^1\) Department of Material Engineering, Engineering of College, University of Diyala, 32001, Baqubah, Diyala, Iraq
\(^2\) Department of Civil Engineering, Engineering of College, University of Diyala, 32001, Baqubah, Diyala, Iraq
\(^3\) E-mail: msc_jgj_katma7@yahoo.com

Abstract. 3D explicit technique based on finite element analysis is usually applied for solving the nonlinear problems in metal forming processes such as wire drawing. The mass scaling percentage that related with stable time increment has substantial influence for attaining the optimum simulation results. In this article, the drawing process of A304 stainless wire utilizing analytical and numerical approach without mass scaling was developed to estimate and validate the obtained drawing stresses using different reduction of area. Then, 3D explicit models based on finite element analysis was run using various mass scaling at the low and high reduction of area 12 and 27\% for displaying the analysis time, equivalent plastic strain (PEEQ), and drawing stress. The results exposed that the appropriate increase of mass percentage corresponding to the target time increment can be selected for reducing the time of wire drawing analysis to 53 and 50\% at reduction of area 12 and 27\% respectively. Although the PEEQ and drawing stress had little increase when the mass percentage raises however, it should be taken into consideration through the design of the wire drawing process. Therefore; the mass scaling value must be carefully adopted.

Keywords: Finite element analysis; Drawing stress; Mass scaling; Target time increments; Equivalent plastic strain

1. Introduction
The wire drawing process is widely used in manufacturing operations for cable production with the various size which utilized in the electrical and electronic applications. In this process, the wire diameter is formed through the carbide die which has a semi cone angle and bearing length. The large contact between the die surface and wire surface as well as the plastic deformation due to the reduction of area are difficult tasks that must be controlled during the forming process [1].

In the previous works, many experimental, analytical and numerical solutions were elucidated through conducting wire drawing in terms of drawing force, process parameters, residual stresses, and wires defects. Vega G. et al. [2] found a drawing force of copper wire based on half cone angle, area reduction, and friction coefficient using experimental and numerical model. They indicated the friction coefficient is the most important parameter affected drawing force. Hassan et al. [3] considered the effect of the drawing parameters on the drawing force of Al-1100 wire according to both the slab and finite element technique. In addition, the influence of the die geometry on the drawing force of steel...
Based on theoretical procedure was performed by Tintlecan M. et al. [4]. Moreover, Moharana B. et al. [5] obtained the optimum value of friction coefficient during the drawing process of aluminum wire rod utilizing the finite element analysis. Boca I. et al. [6] carried out the finite element method for pulling steel wire to describe the effect of die parameters on the drawing force. Circumferential residual stresses according to a new die geometry were predicted by Ripoll, M. et al. [7] using the finite element method for drawing and bending of Tungsten wires sequentially. Lee S. et al. [8] evaluated the temperature raise during the drawing process on the mechanical properties of the final steel wire. The study revealed that excessive temperature leads to an increase in plastic deformation. Drawing and fracture parameters of magnesium alloy wires based on the heated die were correlated by running a finite element model for improving the yield stress and ductility [9].

Explicit dynamic technique based on finite element analysis is developed efficiently in order to solve the convoluted problems i.e. the nonlinear behavior and the large deformations of material during forming processes [10-12]. The time integration of the simulation is higher since the stable time increment is smaller than the critical time that depends on the smallest dimensions of the mesh element. The mass scaling was used based on numerical analysis to reduce the analysis time of metal forming analysis [13,14]. Some studies addressed the application of mass scaling techniques in deep drawing and rolling process for reducing the analysis time. Min W. et al [15] analyzed the hot rolling process by finite element method and run a mass scaling technique according to the ABAQUS explicit dynamic while Li L. et al [16] developed the same model for revealing the effect of mass scaling on the cold roll-bating process.

Although the mass scaling is the active technique for manufacturing processes and quasi-static analysis which include a long contact problem with low velocity, the effect of mass scaling for the 3D wire drawing problems was not taken into consideration. In the wire drawing process using the 3D explicit dynamic technique, the formed wire by a die is too long compared to the drawing velocity which needs a huge time for finding the results. Therefore, mass scaling through the time scaling is selected for decreasing the computational time obtaining with accurate results solutions of the wire drawing simulation. In the current article, the wire drawing of A304 stainless steel is analyzed at different reductions of area (R%) using the numerical and analytical procedures to determine the drawing stresses that are considered for the validation of results. The effect of mass scaling based on target time increments (TTI) on the time of analysis, equivalent plastic strain (PEEQ), and drawing stress are extensively studied using 3D finite element simulation at the low and high reduction of wire dimensions R=12 and 27%.

2. Material behavior of 304 stainless steel wire

The behavior of a material has an essential role in determining stress and strain during the wire drawing process. In this work, 304 stainless steel was picked out as a material of wire product. Table 1 reports the chemical composition of stainless steel grad 304. Table 2 introduces the mechanical properties of the wire material.

| Element | C | Mn | P | S | Si | Cr | Ni | N | Fe |
|---------|---|----|---|---|----|----|----|---|----|
| Wt%     | 0.08 | 2.00 | 0.045 | 0.030 | 0.75 | 18.00-20.00 | 8.00-12.00 | 0.10 | 67-71 |
| max     | max | max | max | max | max | 20.00 | 12.00 | max |

| Density | Module elasticity | Yield tensile stress | Ultimate tensile stress | Poisson’s ratio | Percent elongation |
|---------|-------------------|---------------------|------------------------|----------------|-------------------|
| 8.0 g/cm³ | 193 GPa | 205 MPa | 515 MPa | 0.285 | 40% |
The relationship between true stress vs true strain is calculated using Holloman’s equation as shown in equation (1).

\[ \sigma = K \varepsilon^n \]  

(1)

Where \( \varepsilon \) is the plastic strain, \( n \) is a coefficient of strain hardening and \( K \) represents the strength coefficient for 304 stainless steel, the \( n \) and \( K \) are taken 0.52 and 1137 MPa respectively [19]. Figure 1 illustrated the true stress vs. true plastic strain based on Holloman’s equation.

![Figure 1. True stress vs. true plastic strain of 304 stainless steel.](image)

3. Analytical approach of the wire drawing process

The slab technique is developed to estimate drawing stresses with various reduction of area \( R\% \). In this technique, the drawing stress is calculated by the effect of the reduction of wire diameter (homogenous deformation), frictional resistance (frictional deformation), and flow direction (redundant deformation) [3] as demonstrated in equation (2) [20]. Where \( A_o \) and \( A_f \) represent wire areas before and after drawing respectively while \( \mu \) and \( \alpha \) define as friction coefficient and half die angle in order. The flow stress \( Y \) can be obtained according to the equation (3).

\[ \sigma_d = Y \ln \left( A_o/A_f \right) \left( 1 + \mu \cot \alpha \right) \]  

(2)

\[ Y = \left( K \varepsilon^n \right) / \left( 1 + n \right) \]  

(3)

\( K \) and \( n \) are the strength coefficient and the coefficient of strain hardening as mentioned in section 2, \( \varepsilon \) is a strain at the reduction of the area and it can be identified by equation (4) where \( R \) is the amount of the reduction of area.

\[ \varepsilon = \ln \left( 1/R \right) \]  

(4)

For all wire drawing models, the initial diameter of the wire \( d_o = 5 \text{ mm} \), friction coefficient \( \mu = 0.1 \), and half cone angle \( \alpha = 9^\circ \) are applied while other parameters are given in Table 3 where \( A_f \) and \( d_f \) represent final cross section area and diameter of wire after drawing in order.

| \( R\% \) | \( A_f \) (\text{mm}^2) | \( d_f \) (\text{mm}) | \( \varepsilon \) (\text{mm/mm}) | \( Y \) (\text{N/mm}^2) |
|---|---|---|---|---|
| 12 | 17.2700 | 4.690416 | 0.127833 | 256.6681 |
| 17 | 16.2287 | 4.555217 | 0.18633 | 312.2219 |
| 22 | 15.3075 | 4.41588 | 0.248461 | 362.6198 |
| 27 | 14.3262 | 4.272002 | 0.314711 | 410.0444 |
| 32 | 13.3450 | 4.123106 | 0.385662 | 455.7689 |
4. Numerical approach of the wire drawing process
The commercial ABAQUS software is utilized for simulating the wire drawing process. For all simulations at various R%, the dimensions and parameters of die geometry were taken similar to the analytical method as mentioned in section 3 and reported in Table 3. The material properties were given in Table 2 and elasto-plastic behavior of selected material was drawn in Figure 1.

In this work, the coefficient of friction 0.1 is chosen for steel wire [21]. For the 3D wire drawing model, initial and step boundary conditions are run for describing the material movement during the rigid die. The initial boundary condition represents the die fixing in the direction (U1=U2=0) while another direction is free (UR3≠0). The step boundary condition called step load illustrates the speed drawing at the head of the wire. Through pulling the wire in drawing direction, the speed drawing (v) for all models is 100 mm/s. To maintain a high-quality mesh throughout an analysis, Arbitrary Lagrangian- Eulerian (ALE) was applied during the adaptive mesh domain by given the frequency 10 and remeshing sweeps per increment 3. The element type of the wire drawing model of C3D8R is picked out which refers to the 8-node linear brick, reduced integration, hourglass control. For the initial wire, an approximate element global size of 0.1 with the number of elements 1500 are modeled. The mesh size of the die is 0.12 is put while the different number of elements is determined due to the change in the dimensions that depend on the R%.

5. Mass scaling in explicit numerical analysis
In explicit technique, the dimensions of the model and material properties are responsible for determining the size of time increment without resorting to the complexity of the geometry as in the implicit technique. Moreover, the cost of CPU completely depends on the size of the time increment [13,22,23]. The time step is small to keep the analysis in a stable state by estimating the output at the first step that is run for calculating the results at the next step. This procedure continues (step by step calculations) until the final solution at the final step. For this reason, the explicit technique should be stable during the analysis process and the critical time ΔTc is larger than the stable time increment ΔT [24]. In equation (5), Tmin represents the eigenvalue of the small element while the eigenvalue of the large element is denoted by ¯ωmax [15,22,25]. The number of time increments can be found by equation (6) where T known as the actual time of the forming process and N is the number of time increments [16]. The stable time increments ΔT is determined automatically by ABAQUS program while the critical stable time is calculated by equation (7).

\[ \Delta T \leq \Delta T_c = \left( \frac{T_{\text{min}}}{n} \right) = \left( \frac{2}{\omega_{\text{max}}} \right) \]

\[ N = \frac{T}{\Delta T} \]

\[ \Delta T_c \approx \left( \frac{L_{\text{min}}}{C_d} \right) \]  

where \( L_{\text{min}} \) is the smallest dimension of element and \( C_d \) is defined as the speed of the wave propagation in the material. It can be estimated the value of \( C_d \) in terms of the constants of the material (\( \lambda_o \) and \( v_o \)) through the equation (8). These constants can be calculated by Eqs. (9) and (10) respectively where \( E \) is the young's modulus of the material, \( \rho \) material density, and \( v \) represents Poisson’s ratio. All these values were given in Table 2.

\[ C_d = \sqrt{\left( \lambda_o + 2v_o \right) / \rho} \]  

\[ \lambda_o = E\nu/[\left(1 + \nu\right)\left(1 - 2\nu\right)] \]  

\[ v_o = E/[2\left(1 + \nu\right)] \]

The mass scaling means the increase in the material density by adding the mass to an element without effects on results calculations. The purpose of the mass scaling is to improve the computational efficiency of the analysis. In ABAQUS software, different ways can be performed for applying the mass scaling. The most frequent types in manufacturing technology are mass scaling by factor and by target time increments TTI [13,14,22,26]. In this study, mass scaling utilizing TTI is selected for the full model at the starting of the step.
6. Results and discussion

6.1 Analytical and numerical of drawing stress results

The aim of utilizing the analytical method is to show the models verification through the comparison of the results between the slab and finite element analysis as displayed in Figure 2. The drawing stress was determined at the different reduction of area R% with half die angle $\alpha=9^\circ$ and friction coefficient $\mu=0.1$. The finite element results of drawing stress were obtained for one pass without using mass scaling. It can be observed that the results of the analytical and numerical method are close to each other and drawing stress surges when the reduction of area is raised. This is a good calibration that means the initial boundary condition for finite element models are correctly defined.

![Figure 2. Comparison results between analytical and numerical method.](image)

6.2 Energy Balance of wire drawing process without mass scaling

Figures 3(a and b) demonstrates the energy balance of the wire drawing process without mass scaling at R=12 and 27% respectively. The work done by an external force (E.W) represents the energy needed for drawing of the wire. The internal energy (I.E) signifies the energy consumption due to the plastic deformation. In addition, the generated heat during the sliding between the wire and die surfaces creates the frictional dissipation energy (F.E) [27]. The combined of I.E and F.E approximately equivalent to the applied work that produced from the external force (E.W). Theoretical kinetic energy (K.E) is $4.71 \times 10^{-3}$ mJ at velocity 100 mm/s while its predetermined value by ABAQUS Software is $4.1 \times 10^{-3}$ mJ and $3.4 \times 10^{-3}$ mJ at R=12 and 27% in order. The variation in K.E due to the increase in R% directly affects the field of the drawing velocity in forming zone. The strain energy (S.E) and total energy (ET.E) are small compared to the E.W and I. E as shown in Figure 3a. and 3b.
6.3 Mass scaling and time of analysis

Table 4 presents the time of analysis (CPU time) at the CPU processor of 2.20 GHz intel type which applied for all simulations. It can be observed that the increase TTI results in raises the percent of mass increase (m%) and decreases the CPU time with the selected values of the R at forming time $T = 0.06\,\text{s}$. Also, it can be noticed that the two lowest values of TTI ($1.75e^{-8}$ and $2.25e^{-8}$) generate small raise of m% with the two different values of R%. On the other hand, the two biggest value of TTI ($7.00e^{-8}$ and $1.20e^{-7}$) gave a large increasing in m%. However, the TTI at $3.45e^{-8}$ leads to optimum results where the CPU time decreases around 53% and 50% at R=12 and 27 % respectively.

| Target time increments TTI (s) | CPU Time (min) | m (%) | CPU Time (min) | m (%) |
|-------------------------------|---------------|-------|---------------|-------|
| R=12%                         |               |       |               |       |
| $1.75e^{-8}$                  | 890           | $1.11e^{-2}$ | 945           | $1.47e^{-2}$ |
| $2.25e^{-8}$                  | 780           | $8.39e^{-2}$ | 747           | $1.12e^{-1}$ |
| $3.45e^{-8}$                  | 645           | $4.82e^{-1}$ | 468           | $6.37e^{-1}$ |
| $7.00e^{-8}$                  | 421           | 2.64   | 231           | 3.49  |
| $1.20e^{-7}$                  | 205           | 8.17   | 136           | 10.08 |

Due to the adding non-physical mass that can affect the accuracy of results, the energy balance history should be screened. Further, the E.W and I.E must be close to each other i.e. the differences between them must be too small and the ratio of (K.E/I. E) should be less than 5% [15]. Furthermore, F.E should be taken into consideration with I.E to be close to the E.W. Hence, Figure 4 (a and b) proves that the energy differences of (E.W-I. E-F. E) equal to small values for all time steps and (K.E/I. E) is smaller than 5%.
Figure 4. Differences of (E.W - I.E - F.E) and (K.E/I.E) at TTI of 3.45e⁻⁸ at (a) R=12% and (b) R=27%.

6.4 Mass scaling and equivalent plastic strain PEEQ

Figure 5 (a and b) depicts the relationship between mass increase (m%) and maximum equivalent plastic strain (PEEQ) that generated during the wire drawing process at time step 0.06 s with both selected values of R =12 and 27% respectively. It can be seen that the mass scaling has a significant effect on PEEQ. The minimum error ratio of PEEQ at R= 12% can be obtained at m= 0.482% and TTI= 3.45e⁻⁸. However, the minimum error ratio of PEEQ at R=27% can be recorded by m=0.637% and TTI= 3.45e⁻⁸.

Figure 5. Mass scaling effect on equivalent plastic strain at (a) R=12% and (b) R=27%

It can be detected from Figures 6 and 7 that the increase in m% leads to the increase in PEEQ. Also, the R=27% produces larger PEEQ than R=12% because of the increase in energy of plastic deformation due to the increases in the reduction of wire dimensions.
6.5 Mass scaling and drawing stress

Effect of mass scaling on drawing stress with R=12 and 27% is introduced in Figure 8 (a and b) respectively. The increase in drawing stress value should be taken into concern during the design of the process, since it may lead to failure of the material or produces defects in the final product. So, the m% corresponding to the TTI should be carefully selected for obtaining the accurate results with the minimum error. In case of R=12 %, as illustrated in Figure 8a, the m=0.482 % at TTI=3.45e−8 leads to the increases the drawing stress 0.8% with the reduction of analysis time 53%. While for R=27%, the drawing stress increases about 0.6% at m=0.637% with the reduction of analysis time equal to 50% and TTI=3.45e−8, as seen in Figure 8b.

Figure 6. PEEQ distribution at R=12% (a) without (m%), and (b) with (m= 0.428%).

Figure 7. PEEQ distribution at R=27% (a) without (m%), and (b) with (m= 0.637%).

Figure 8. Mass scaling effect on drawing stress at (a) R=12% and (b) R=27%.
7. Conclusion

In this work, finite element analysis was verified with slab analysis results in term of drawing stress at the different reduction of area R% for the stainless steel wire. The energy balance without applying mass scaling was implemented and it was indicated that the generated energy by the friction condition F.E should be taken into consideration with internal energy I.E for calculating the work done applied by the external force E.W. Based on 3D explicit dynamic analysis at various mass scaling, the results of energy history showed that target time increments of TTI=3.45e^{-8} is the appropriate value to reduce analysis time for high and low reduction of area. The differences calculation between E.W, E.I, and F.E in addition to the computed ratio between K.E to the I.E which is smaller than 5% have confirmed that the obtained results are acceptable. The time of wire drawing analysis using R=12 and 27% can be reduced around 53% and 50% respectively. The max PEEQ has differentiated values when the mass scaling raises. Therefore; the wrong choice of mass scaling may lead to defects in the final product. The drawing stress increases with increasing of mass scaling for both adopted values of R= 12 and 27%. The increase in drawing stress was 0.6% and 0.8% at the high and low reduction of area in order.

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