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AISI 1010 çeliği için proses parametrelerinin sabit mandrel ile soğuk boru çekme işlemine etkilerinin sonlu elemanlar analiziyle incelenmesi

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ÖZ

Bu çalışmada, sonlu elemanlar analizi kullanılarak, sabit mandrel ile soğuk boru çekme işleminin benzetimi yapılmış olup, kesit daralma oranının, yarı kalıp açısının, yarı mandrel açısının ve sürtünme katsayılarının çekme gerilmesine etkileri araştırılmıştır. Sonlu elemenlar modeli, %16 kesit daralmasındaki deneysel verilerle doğrulanmıştır. Netice olarak, yarı kalıp açısının plastik şekil değişimine etkisi yarı mandrel açısından daha büyük olmuştur. Sebebi ise kalıp açısının büyüklüğünden kaynaklanmaktadır. 12^{o}'lik yarı kalıp açısı bütün sürtünme değerleri için minumum çekme gerilmesini vermektedir. Sabit konik mandrel ile boru çekme işleminde 7^{o}'lik yarı kalıp açısı için $2\text{-}4^{o}$ aralığındaki yarı mandrel açısı kullanılmalıdır. Deneysel ve sonlu elemanlar analiz sonuçlarının uyum içinde olduğu görülmüştür.

Anahtar Kelimeler: Soğuk boru çekme, Sonlu eleman analizi (FEA), çekme gerilmesi, yarı kalıp açısı, yarı mandrel açısı

Effect of the process parameters on cold tube drawing with a fixed plug using finite element analysis for AISI 1010 steel

ABSTRACT

In this present work, finite element analysis (FEA) is applied to simulate cold tube drawing process with a fixed plug for AISI 1010 steel tube. The effects of reduction of area, semi die angle, semi plug angle, and friction coefficient on drawing stress are studied. The finite element model is successfully validated with the experimental data at reduction of area 16%. Results indicate that a good agreement between the experimental and the finite element analysis (FEA) is found. Consequently, the effect of semi die angle on plastic deformation is larger than the semi plug angle because of the bigger size of the semi die angle. Semi die angle of 12° gives minimum drawing stress for all coefficient of frictions. A semi plug angle between 2° and 4° should be used in tube drawing process with a conical fixed plug when semi die angle is equal to 7^{o}.

Keywords: Tube cold drawings; finite element analysis (FEA), drawing stress; semi die angle; semi plug angle.

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1. INTRODUCTION

Tube drawing is one of the technologically important metalworking processes to reduce tube thickness where outside is formed by a drawing die and the inside by a plug or a rod. There is a significant increase in the use of tube products in mechanical applications. However, the quality of tube products and a good surface finish of inner and outer diameters have been concerned. High quality and good surface finish tube products are big challenges in cold tube drawing processes. Basically, four types of tube drawing processes can be considered to reduce outer and inner diameters of the tube. For all of the types, die diameter is used to calibrate the outer diameter, while there are also various other techniques are developed to calibrate inner diameter of the cold drawn tube. These four processes are follow: drawing without a mandrel (tube sinking), drawing over a stationary (fixed) mandrel (plug), drawing over a floating plug, and drawing over a moving mandrel [1]. In this study, the drawing over a stationary mandrel (plug) as shown in Figure 1 was considered. It has been known that finite element analysis (FEA) has been widely used to solve complex metals forming problems. Besides, the rapid technological development in computers field has reduced human effort and cycle time. Although tube drawing process have been taken into consideration by many researchers analytically and numerically, only few researchers have studied cold tube-drawing process experimentally. Because, it is expensive, complex, and requires advanced control during the drawing process.

Tube drawing with a fixed plug or sometime called tube drawing with a fixed mandrel is used to obtain a good surface finish for both the inner and the outer surface of the final tube.

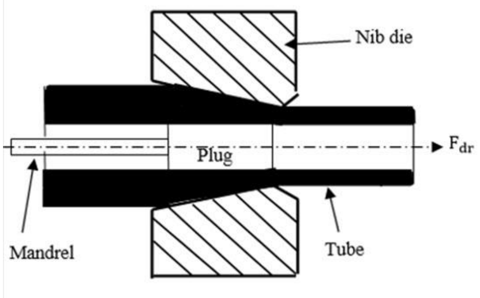

Figure 1. Tube drawing over a stationary mandrel (drawing with a fixed plug)

Tube drawing with a floating plug was studied by Joachim and Endelt [2] using finite element software LS-DYNA with implicit time integration. The study showed that both the length and shape of bearing channel depend on the drawing force with conventional tooling [2]. In another study, Beland et al. [3] used LS-DYNA to determine optimization of tool geometry for reducing stress level for 6063 T4 by a sinker die, a drawing die, and cylindrical plug. The study reveals that three tubes can be drawn at the same time up to maximum length of 12 m at different tube diameters and wall thicknesses. Bihamta et. al [4] studied the effects of die angle, mandrel angle, and fillet radius on the max tube deformation using D-optimal method experimentally and finite element method. AL 6063-0 tube was produced at variable thicknesses. The study proved that the finite element method is an active tool to determine optimum geometry. Cold tube drawing with and without plug was studied by finite element method to improve the quality of finish surface for Cobalt-Chromium alloy tubes [5]. Physical parameters have been analyzed experimentally to identify the constitutive equation, the inelastic heat friction, and the convection of heat transfer. The outcome of the study is that the temperature variation and interface properties affect the local behavior of material significantly. Several mandrel and different diameters have been examined to estimate tube drawing limit and to evaluate ductile failure criteria in a series of drawing test by applying experimental method. SEM images were determined and evaluated. Linardon et. al [6] simulated local stress and strain data that represent a tool of the process optimization. Optimum die profile according to the Arc and Bezier curves was designed by Ref [7] to estimate maximum drawing force and the mean effective strain deviation along the tube thickness. The results showed that the method of die design can give better results of the drawn tubes. Trana et. al [8] developed numerical and experimental approach to determine the drawing efficiency of 6082-0 temper aluminum alloy for cartridge tubes manufacturing. Tensile, compression, and shear tests for the various samples were conducted. The plastic strain and graph of material envelope for zero Lode parameters were determined. Finite element model using 3D LS-DYNA was also improved using a solid element type. The study verified that the drawing degree can be safely determined while processing cartridge thin tube subjected to inner pressure.

In this research, the effects of reduction of area, semi die angle, semi plug angle, and friction coefficient on drawing stress were studied by reducing tube dimensions (outer diameter, inner diameter, and thickness). Cold tube drawing with a straight plug was done experimentally by a chain assisted machine. The process was performed under lubrication. Finally, the process was modeled by FEA and was validated with the experimental data at reduction area of 16%. The finite element model was used to simulate different reduction of area, semi die and semi plug angles at 23%. Several coefficients of friction; 0.1, 0.125, and 0.15 with constant of velocity were tested. In all our simulations, a commercially available finite element software ABAQUS^{TM} was used.

2. DIE AND PLUG GEOMETRIES

The die geometries consist of semi die angle, bearing length, and entry radius as displayed in Figure 2. Semi die angle is defined as the slant of die wall toward to the drawing direction [9]. In this study, different semi die angles, fix bearing length of 7 mm and die entry radius of 7 mm were selected for outer diameter reduction analysis when the reduction of area 23%.

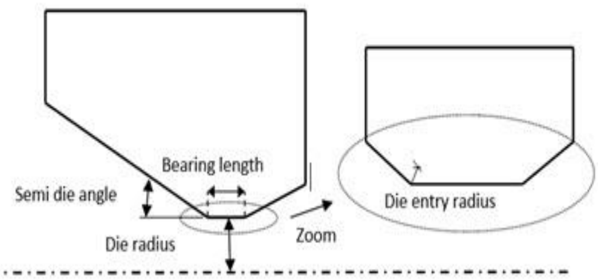

Figure 2. Die geometries

Straight and conical plug geometries were used for deformation of inner diameter. The conical plug includes semi plug angle and nib as shown in Figure 3. Semi plug angle is the slant of plug wall at drawing direction. It has a major role to obtain a good surface finish of inner diameter of drawn pipe.

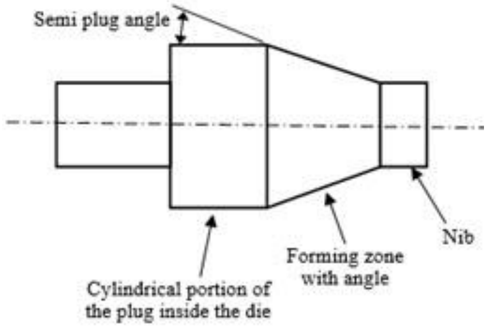

Figure 3. Conical plug geometries

In tube drawing process with a fixed plug, the nib die and plug are very important because of the contact between the internal surface of the die and external surface of tube and the contact between external surface of plug and the internal surface of tube during the drawing process. Nib die and plug are made of tungsten carbide, which has strong corrosion resistance. The mechanical properties of tungsten carbide are density of 15500kg/m^3, Poisson's ratio of 0.2, and Young's modulus of 650 GPa.

3. EXPERIMENTAL WORK

The chain drawing machine did not have load cell, for this reason, a compression test was used to measure force vs. displacement at low velocity. The initial outer and inner diameters of the initial tube are 78 and 71 mm with the initial length for the tube is 70 mm. After compression, the tube moves to 20 mm for R = 16%. The tube has a thickness of 3.5 mm. The tube was reduced to outer diameter of 76 mm, inner diameter of 70 mm, and thickness of 3 mm.

4. FINITE ELEMENT ANALYSIS

Tube drawing with a fixed plug was modeled by finite element analysis (FEA) software, ABAQUS^{TM}6.14-2. For reduction of area 16%, one model was simulated to detemine compression force vs. displacement at semi die angle of15°, semi plug angle of 0° and friction coefficient of 0.1. The geometry was modeled as an axisymmetric to determine the drawing stress. Several reductions of area of 16, 19.4, and 23% were applied. Semi die angles of 5°, 7°, 10°, 12°, and 15° were studied. Semi plug angles were selected as 0°, 1°, 2°, 3°, and 4°. The coefficients of the friction 0.1, 0.125, and 0.15 were used. The mechanical properties and true stress vs. effective plastic strain values of AISI 1010 steel are presented in Table 1 and Table 2, respectively.

Table 1. Mechanical properties of AISI 1010 steel

Density (g/cm3)	7.722
Young's Modulus (*E*) (GPa)	200
Poisson's Ratio	0.285
Yield Strength (MPa)	560
Ultimate Tensile Strength (MPa)	611
Elongation %	20
Hardness	132 HBW

Table 2. True stress and effective plastic strain of AISI 1010 steel

True stress (MPa)	Effective plastic strain (mm/mm)
563.0296	0
566.4145179	7.53454E-05
576.9544903	0.000590789
587.2014622	0.00147812
602.9924593	0.00329494
610.3349758	0.005004866
613.7224689	0.005953277
615.2229355	0.006735149
617.1610511	0.007879191
619.3638319	0.009385779
620.7268214	0.010837115
621.6564464	0.011986002

In the finite element simulation, a step was defined with proper time increment therefore, solution was easily converged. Dynamic/Explicit solution was used due to the model has complex contact interaction. Arbitrary Lagrangian Eulerian ALE meshing combines the features of pure Lagrangian analysis and pure Eulerian analysis. So, it can be used with explicit, dynamic that allows to maintain a high-quality mesh throughout dynamic analysis and makes the mesh move independently of the material when occurring large deformation or losses of material with the mesh topology remains unchanged. The frictional constraints were defined with the interaction option. In procedure of Explicit/Dynamic, surface-to-surface (explicit) was developed to create an interaction. Finite sliding with a penalty contact method was selected for all contacts to resolve tangential behavior of a mechanical contact. In this method, the compressive force is proportional to the penetration of the material, using the basic concept of the Coulomb friction model. Contact interaction property was selected to define normal behavior (hard contact) and tangential behavior with friction coefficients of 0.1, 0.125, and 0.15. Boundary conditions were applied to move material between the die and the fixed plug. First, for initial condition the die and the fixed plug were fixed at all direction (U_1=0, U_2=0, $UR_3 \neq 0$). In the second step, velocity 4.25 m/min was applied. It is known fact that the accuracy of simulation results strongly depend on selected element type and mesh size. In this study, a 4-node bilinear axisymmetric quadrilateral, reduced integration, hourglass control element was used as seen in Figure 4.

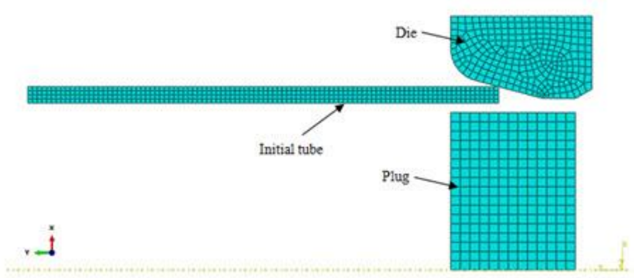

Figure 4. Meshing of axisymmetric tube drawing process with a fixed plug

5. RESULTS AND DISCUSSION

5.1 Model Validation

First, the proposed model was validated. It was explained earlier that experimental data was measured in order to validate the proposed model. For this reason, compression forces were compared as shown in Figure 5. The figure displays a comparison between the experiment and the finite element results for the case of 16% reduction of area; semi die angle; 15°, semi plug angle; 0°, and the coefficient of friction was 0.1. Based on the comparison, it is clear that a similar compression force vs. displacement diagram was determined. The results show that the experimentally and numerically determined compression forces were 409.44 and 432.212 kN, respectively corresponding displacements of 19.99 and 20 mm. This outcome clearly proves the validation of the model. The difference between two forces was quite small.

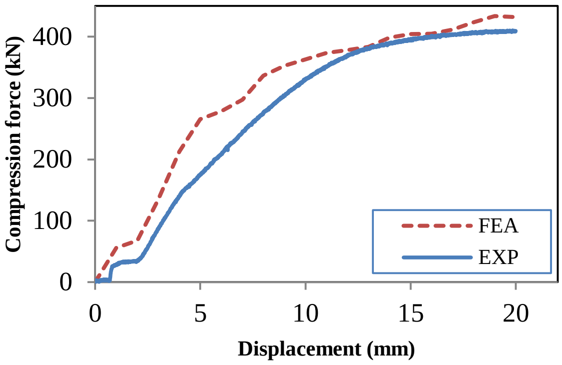

Figure 5. Comparison between experimental and FEA results

5.2 Finite Element Results

5.2.1 Effect semi die/plug angles on plastic deformations

Figure 6a and 6b show equivalent plastic strain (PEEQ) distribution. In Figure 6a, semi die angle is 12°, semi plug angle is 0°, and coefficient of friction is 0.1 while in Figure 6b, semi die angle is 7°, semi plug angle is 4°, and coefficient of friction is 0.1.

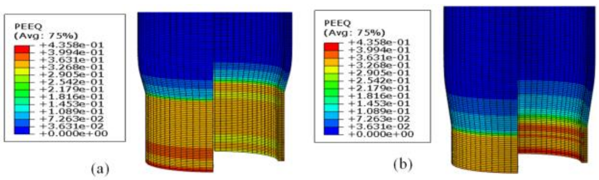

Figure 6. PEEQ axisymmetric finite element models (a) semi die angle of 12° and semi plug angle of 0° (b) semi die angle of 7° and semi plug angle of 4°

In Figure 6, it is quite obvious that there is a clear difference in plastic deformation for (a) and (b) due to the change in semi die/plug angles. The plastic deformation occurs as a result of dislocation motions that represent a linear defect in the crystal structures. A preferred orientation is produced since the crystallographic directions gradually rotate toward more stable orientations that represent drawing direction and this lead to isotropic material transforms to anisotropic [10]. The effect of semi die angle is larger than the effect of semi plug angle on plastic deformations due to the increase in plasticity (higher dislocation density) that take place in contact region. In Figure 6a, it can be seen that the plastic deformation of the outer surface of the tube is larger than the inner surface of the tube due to the high effect of semi die angle. In Figure 6b, it can be observed that the effect of the semi die angle is larger than the semi plug angle. So that, the plastic deformation at the inner surface of the tube is the largest.

5.2.2 Effect reduction of area on drawing stress at different friction coefficient

Three reduction of area were selected as (16, 19.4, and 23%) with semi die angle 15°, semi plug angle 0° and coefficients of friction 0.1, 0.125, and 0.15 as displayed in Figure 7. It can be seen that the drawing stress increases with increasing reduction of area for all friction coefficients due to the increase energy consumption at the inlet and the outlet for the forming area and this leads to the increase in the plastic deformation.

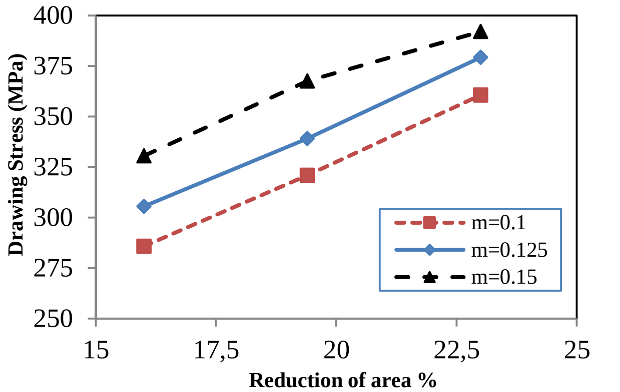

Figure 7. Relationship between the drawing stress and the reduction of area at different friction coefficients

5.2.3 Effects semi die angles on drawing stress at different coefficients of friction

The effect of semi die angle on drawing stress with a constant semi plug angle of 0° at different friction coefficients were plotted in Figure 8. The figure indicates that the drawing stress corresponding to the semi die angles of 5 and 7° recorded larger than other semi die angles because of the increase in dislocation density. Semi die angle produces differences of the friction work, as well as it has the effect of the redundant plastic work of deformation [11]. The redundant deformation represents both of friction and shear deformation and it is a radial strain. Therefore, it can be said that, the semi die angle strongly has a strong effects on drawing stress. The minimum drawing stresses were determined at semi die angle of 12° – 15° for friction coefficients of 0.1, 0.125, and 0.15 correspondingly.

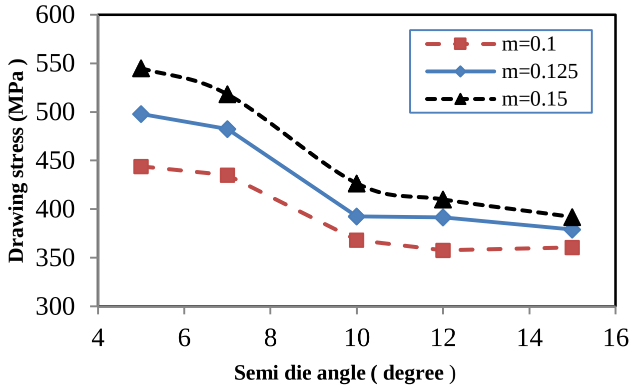

Figure 8. Relationship between drawing stress and semi die angle at different of friction coefficients

5.2.4 Effects semi plug angles on drawing stress at different coefficients of friction

Figure 9 indicates the relationship between semi plug angle and drawing stress at constant semi die angle of 7° at different friction coefficients. The minimum drawing stress was founded with semi plug angle of 0 and 4° while the maximum drawing stress was estimated with semi plug angle 1°. There is a possibility to use semi plug angle between 2 to 4° which is less than the semi die angle that can give very good surface finish for the internal of tube [12].

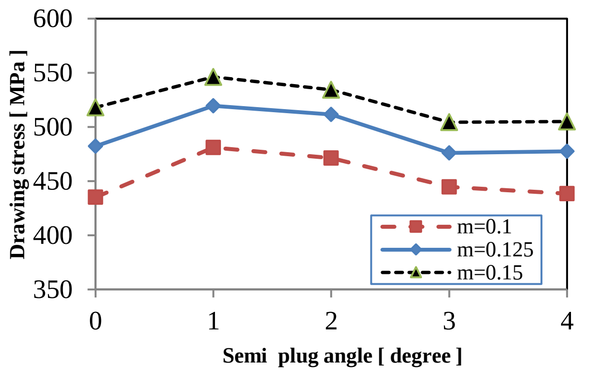

Figure 9. Relationship between drawing stress and semi plug angle at different of friction coefficients

6. CONCLUSION

In this work, the FEA was successfully applied for modeling of tube drawing process with a fixed plug. Different semi die/plug angles at different coefficients of friction were studied in order to determine drawing force and stress. Following conclusions were drawn:

1. An axisymmetric model was successfully validated by experimental data.
2. The effect of semi die angle on plastic deformation was larger than semi plug angle because of the bigger size of semi die angle.
3. Drawing stress increases with increasing reduction of area for all coefficients o friction.
4. Semi die angle of 12 and 15° gives minimum drawing stress for all coefficient of frictions.
5. A semi plug angle between 2 and 4° should be used in tube drawing process with a conical fixed plug when semi die angle is equal to 7°.
6. Drawing stress increases with increasing coefficients of friction for all semi die/plug angles.

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