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Research Paper

Thermo-Mechanical Analysis of Wire Drawing of Copper with PCD die: FEM Study

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ABSTRACT

Thermo-mechanical finite element simulation was used to study Copper wire drawing with PCD die. Effect of drawing angle and coefficient of friction on the distribution of stress and strain on the surface of die and cross-section of wire studied, respectively. Elasto-viscoplastic and elastic models were used to simulate copper and PCD behavior in the axisymmetric model. Regardless of the amount of the drawing angle and coefficient of friction, die entrance and exit exhibit the highest stress on the surface of the die. Maximum amounts of temperature were observed on the surface of the wire exiting the deformation zone. According to the profile of pressure and temperature, the die nib bears the highest amount of pressure and temperature on the die and is susceptible to wear. Analyzing the strain on the wire and stress on the surface of the die showed that at high drawing angles, the distribution of strain on the wire becomes uneven, also stress on the die nib will increase. In contrast, at low drawing angles, the temperature and drawing force rise because of the increase in friction effect. Choosing the drawing angle based on the optimization of the drawing force keeps all mentioned parameters in an acceptable range.

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1. Introduction

Wire drawing is one of the bulk metal forming processes and it aims to symmetrically reduce the cross-section of part by inducing plastic strain [1,2]. Wistreich [1], Siebel [3], and Sachs [4] were the first researchers who studied the process and proposed an equation for the calculation of drawing force considering only the volumetric deformation and friction force in the deformation zone. Yang [2] added friction at the bearing area to the drawing force equation. Avitzur [5-7] tried to consider all affecting parameters and developed Eq. (1) and Eq. (2).

$$\frac{\sigma_f}{\sigma_0}=\frac{\left[\frac{\sigma_b}{\sigma_0}+2f(\alpha)\ln\left(\frac{R_i}{R_f}\right)+\frac{2}{\sqrt{3}}\left(\frac{\alpha}{sin^2\alpha}-\cot\alpha\right)+2\mu\left(\cot(\alpha)\left(1-\frac{\sigma_b}{\sigma_0}-\ln\left(\frac{R_i}{R_f}\right)\right)\ln\left(\frac{R_i}{R_f}\right)+\frac{P}{R_f}\right)\right]}{\left[1+2\mu\frac{P}{R_f}\right]} \quad (1)$$

$$f(\alpha)=\frac{1}{sin^2\alpha}\left(1-\cos\alpha\sqrt{1-\frac{11}{12}sin^2\alpha}+\frac{1}{\sqrt{11.12}}\ln\left[\frac{1+\sqrt{\frac{11}{12}}}{\sqrt{\frac{11}{12}}\cos(\alpha)+\sqrt{1-\frac{11}{12}sin^2\alpha}}\right]\right) \quad (2)$$

where σ_f is drawing tension, σ_0 is yield strength, σ_b is back tension, α is the semi-die angle, μ is coefficient of friction, P is bearing length, and R_i and R_f represent the initial and final radius of wire, respectively.

According to Eq. (1), in a die with a definite semi-die angle and length of bearing zone, the coefficient of friction and yield strength are the parameters that define the accuracy of calculated drawing force [7,8]. Due to the dependency of yield stress on strain rate and temperature [9-14], Vega et al. [15] used strain-rate dependent, and Li et al. [8] used temperature-dependent models to adjust the amount of yield strength. Another group of researchers worked on the estimation of the coefficient of friction based on the accommodation of calculated and measured drawing force. Christopherson and Naylor [9] were the precursors of studying the lubrication and coefficient of friction in wire drawing. Adding the friction force in the bearing area of the die and compensation of yield strength in Avitzur's equation (Eq. 1) reduced the estimation of the coefficient of friction used for drawing force. Nowadays, the range of coefficient of friction is estimated to be between 0.05 and 0.1 for a set of die and wire submerged in lubricant [10,15]. Also, the coefficient of friction in the drawing is dependent on temperature. Haddi et al. [11] used a linear model (Eq. 3) and Vega et al. [12] used power law (Eq. 4) to calculate the coefficient of friction based on temperature.

$$\mu=\mu_0+A\times T \quad (3)$$

$$\frac{\mu}{\mu_0}=A\left(\frac{T}{T_0}\right)^B \quad (4)$$

Having disregarded the effect of temperature change in wire drawing, a set of investigations concentrated on the geometry and material of the die to study the process. Sas-Boca et al. [13] tried to optimize the drawing force using the semi-die angle and bearing length of the die. Jokovic and Djapic [14] optimized the drawing force on PCD, and tungsten carbide dies. Vega et al. [15] investigated the effect of semi-die angle and friction on the drawing force and plastic strain distribution of copper wire drawn by PCD dies. Baumann et al. [16] conducted research on the adjustment of residual stress in wire drawing by modifying die geometry. Haddi et al. [11] investigated the effect of drawing parameters on chevron crack formation in copper wire drawing. This study revealed that chevron crack formation is a stress-temperature-dependent phenomenon.

Since the change in temperature affects drawn wire considerably, a group of studies was devoted to the subject of temperature in wire drawing. Vega et al. [15] studied the effect of drawing speed on temperature and friction. El-Dmoiaty and Kassab [17] calculated the temperature increase in wire drawing. They hypothesized that all of the heat produced by friction in the deformation zone transfers to the wire completely but in practice, this amount is assumed to be a fraction between 80%-90% of the heat [18-20]. By calculating the total energy of the deformation zone and converting it to heat, they calculated the temperature rise for ten different materials. Nowadays, it is known that the deformation energy is the sum of 1. The energy is required for volumetric deformation 2. Shear deformation, and 3. Overcome friction [20].

The results of studying temperature clearly showed that wire drawing is a thermo-mechanical process. Some scientists used thermo-mechanical models to examine the effect of temperature on the mechanical properties of the wire during drawing. Celentano [21] simulated the thermo-mechanical process of copper drawing, neglecting the die properties and assuming the die was a rigid part. Akter and Hashmi [22] used thermal and mechanical characteristics of Polymer material to simulate the process of die-less wire drawing with a viscous polymer. Tiernan and Hillery [23] used thermo-mechanical calculations to study die-less wire drawing with electricity current and tension between capstans. Mohammed et al. [24] used the thermo-mechanical model to study the die-less wire drawing of sus304 and analyze the effect of process parameters on the diameter of the drawn wire. According to the current database, all studies on conventional wire drawing were conducted in the form of separated mechanical and thermal models. Also, investigations on wire drawing neglect the effect of drawing on the die itself. In all studies, the die is considered a rigid part with no properties, and there is no information about the impact of process parameters on the die surface. Another aspect is the coupled effect of thermal and mechanical properties in wire drawing, which has gained little attention among researchers. To cover this area, a thermo-mechanical simulation of wire drawing with conventional dies was carried out. The contour of stress and temperature on both die and wire and their evolution by the change in the coefficient of friction and semi-die angle were studied and analyzed. In the end, optimum process parameters for reaching the best quality in wire and the best working condition on the die have been discussed.

2. Materials and Modeling

The drawing of copper wire with an initial diameter of 0.513 mm and finial diameter of 0.403 mm (r=0.375) has been studied. ABAQUS software was chosen to simulate the process because of its ability to calculate heat transfer [25,26] and mechanical deformation. To model the mechanical properties of the Copper elasto-viscoplastic model (Eq. 5) and Ludwik model (Eq. 6) were used. The elasto-viscoplastic model has been used by other researchers to simulate copper behavior [15-27-28]. According to the experiments by vega et al. [15], viscoplastic and strain hardening parameters of copper wire have been extracted by uniaxial tensile test in different strain rate conditions. These tests must include a quasi-static state. The PCD die is considered to be CTB010. A polycrystalline diamond with the composition of 87% diamond-13% cobalt and 10-micrometer grain size. The mechanical and thermal properties of copper and CTB010 are summarized in Table1.

$$\sigma = \sigma_{y0} + K\left(\varepsilon_p\right)^n \quad (5)$$

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}_p}{\gamma}\right)^m\right]\sigma_{y0} \quad (6)$$

Table 1. Mechanical and thermal properties of copper [15] and CTB-010

Properties	Copper	CTB-010
Yang module (GPa)	117	1000
Density (Ton/M^3)	8.96	4.08
Poisson	0.34	0.1
Specific heat (J/gr°C)	0.385	0.500
Conductivity (w/m°C)	389	560
Quasi-static yield strength (for 0.5 mm dimension-MPa)	166	
M	0.737	-
Y	2.3	-
K (MPa)	484	-
N	0.82	-

The geometry of the die with different semi-die angles and a bearing length of 40% of the final wire diameter was modeled in ABAQUS axisymmetric environment (Fig. 1). Process parameters were adopted from the simulation carried out by Vega et al. [15] to compare the results with that research. The drawing speed of 1000 mm/s and initial temperature of 25 degrees centigrade with a coefficient of friction in the range of 0.05 to 0.1 was chosen for process parameters.

The solver type of Dynamic-Temp-Displacement-Explicit was chosen. The coupled Thermal-Displacement (CAX4RT) element with a mesh size of 0.01 mm was selected to mesh both the die and wire. The results of temperature and stress on the die were collected by defining a path on nodes of the die surface and extracting data from this node list. A similar method was used to obtain strain on the wire section.

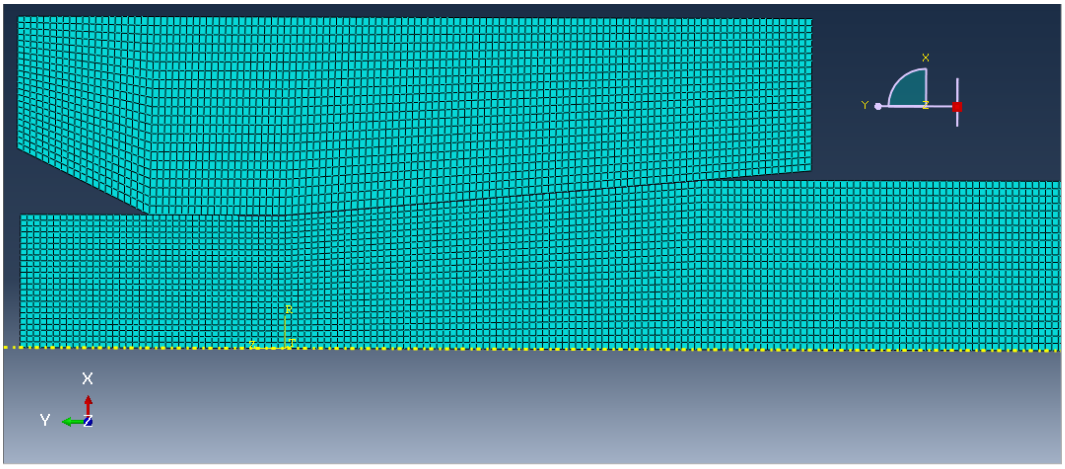


Fig 1. Die and Wire modeled and meshed in axisymmetric mode

3. Verification of Model

Based on the reviewed literature, the finite element model of wire drawing is often verified by measuring three parameters: drawing force, temperature, and residual stress. To determine drawing force, Avitzur's equation (Eq. 1) is the most developed relation for obtaining drawing force and the effect of drawing angle is apparent in this equation. However, its result is lower than the experimentally measured drawing force. In the field of temperature, El-Domiaty and Kassab [17] performed a pervasive study on different materials, and the result of their research for Copper wire was adopted for comparison. For verifying residual stress, the state of the stress (compression or tension) has been reported regardless of its amount by other researchers because the small dimension of the wire hampers experimental measurement of stress.

3.1 Drawing Force

Fig. 2 shows the drawing force extracted from the model for different semi-die angles. Also, the results of Avitzur's equation for different drawing angles and friction coefficients have been plotted in Fig.2. For μ=0.05, the calculated force of Avitzur's equation is less than the FE model, still, in μ=0.1, the results of calculations match the finite element model, very well. There is a slight difference in low angles in μ=0.1.

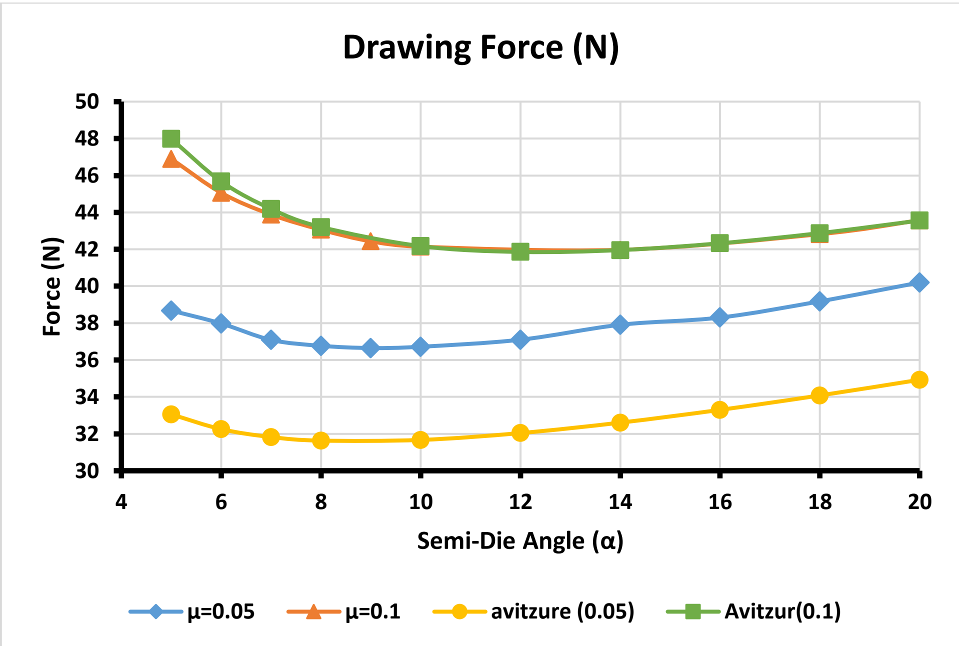


Fig. 2. Drawing force extracted from FE model and calculated by Avitzur's equation (Eq. 1).

3.2 Temperature

Fig. 3 illustrates isothermal regions of wire in the deformation zone. Based on Fig.3, the temperature of the wire increases as it undergoes further deformation in the deformation zone. Accumulating frictional heat on deformation heat causes the surface of the wire at the final deformation stage to be the hottest area in wire drawing. Fig. 4 shows the maximum temperature of wire in the deformation zone with different semi-die angles ranging from 5 to 20 degrees. A comparison of the results of the FE model with the results of El-Domiaty and Kassab (Fig. 6 [17]) shows a good agreement between simulated and calculated results. There is a slight difference, and the reason comes from the assumption that El-Domiaty and Kassab [17] considered all frictional heat transfers to the wire, but in this study, this proportion was assumed to be 90% wire-10% die.

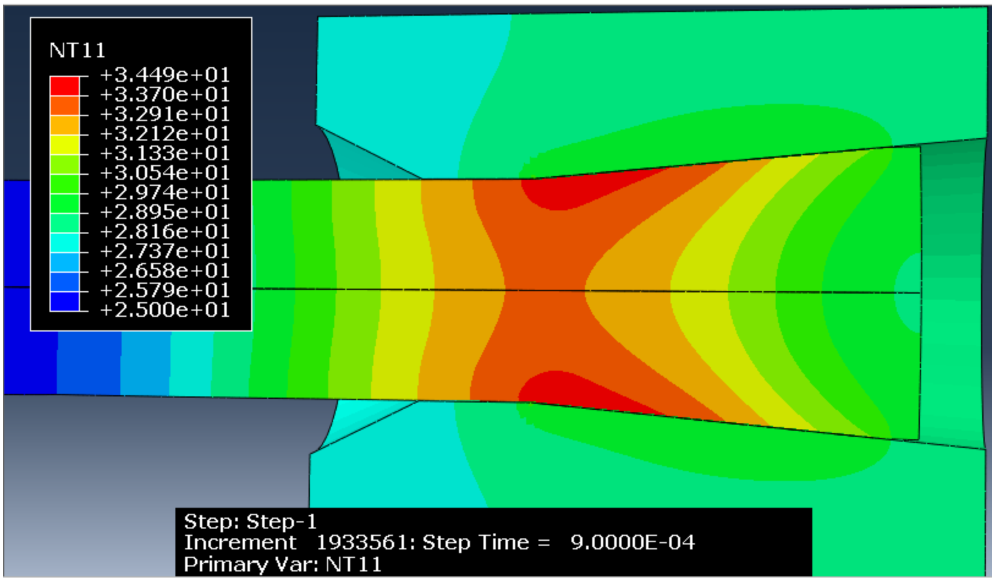


Fig. 3. Contours of temperature on wire and die during drawing. Semi-die angle α=5, coefficient of friction μ=0.05, Drawing speed v=1000 mm/s

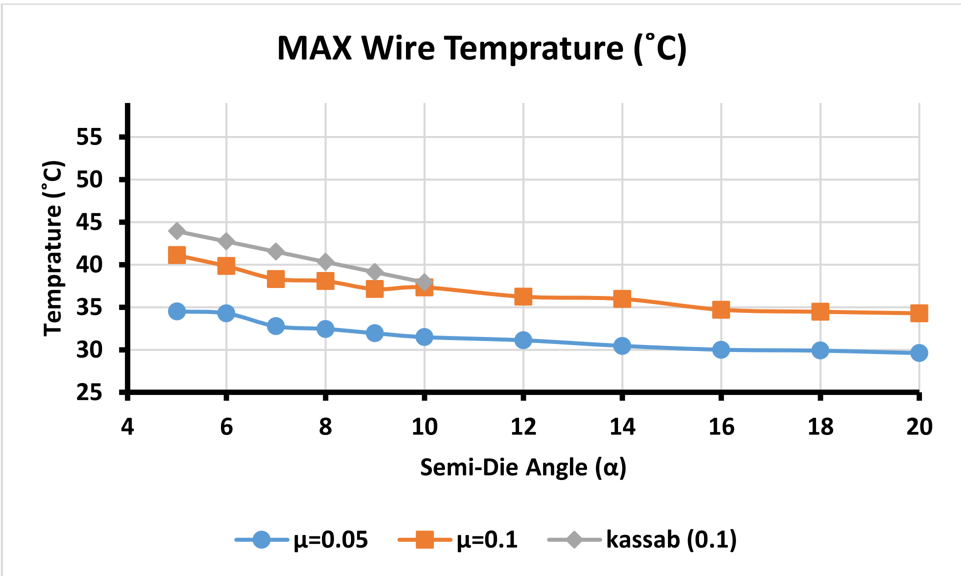
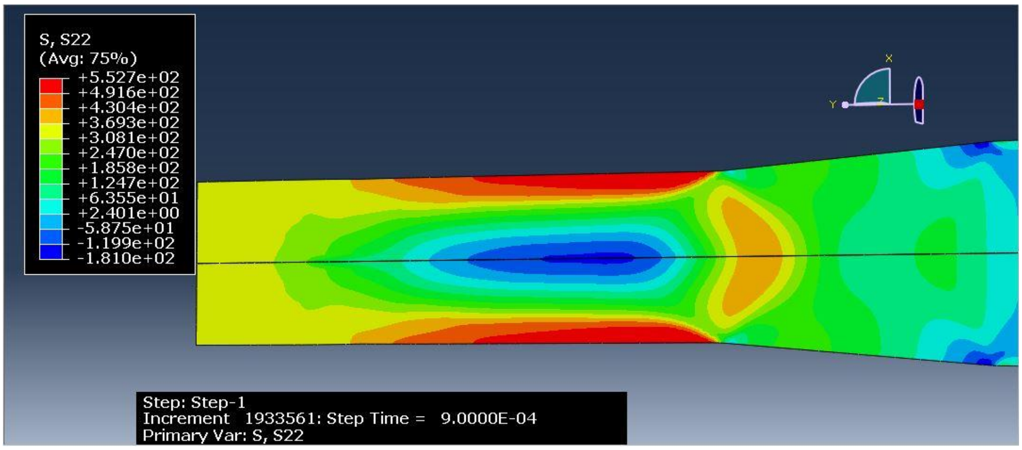


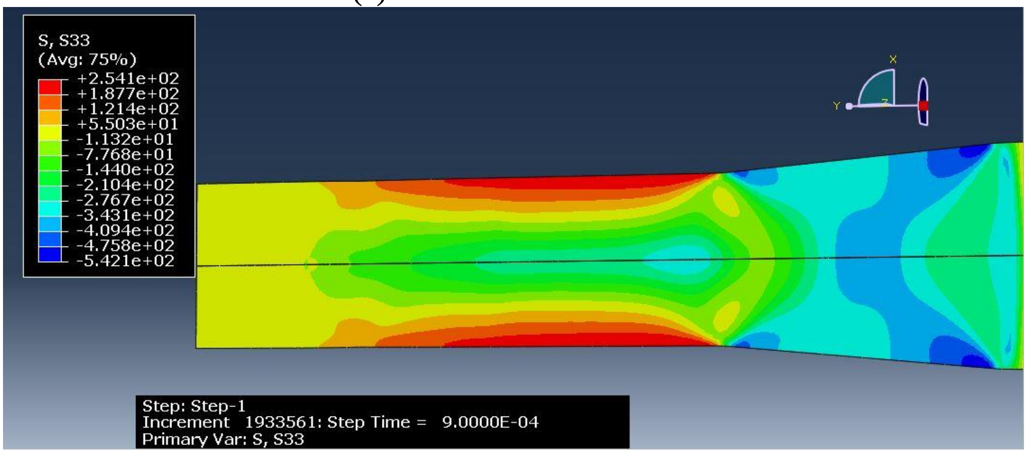
Fig. 4. Maximum observed temperature on wire in term of different Semi-die angles (α) and coefficient of friction (μ)

3.3 Residual Stress

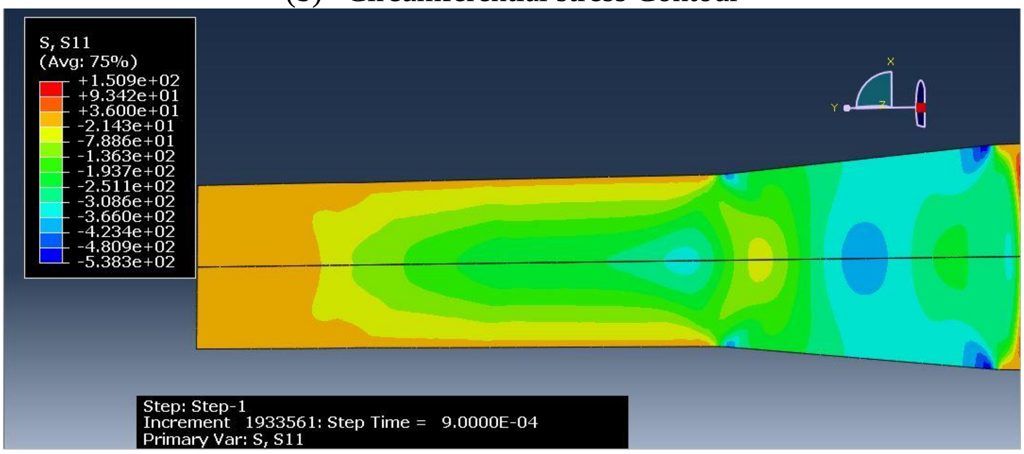
Fig. 5 depicts the components of residual stress in the drawn wire after passing the deformation zone. According to Baumann's Results [16], Axial and Circumferential stress should be tensile at the surface and near the surface and compressive in the axis of the wire. Also, radial residual stress should be compressive in the wire section and zero at the surface.



(a) Axial stress Contour



(b) Circumferential stress Contour



(c) Radial Stress Contour

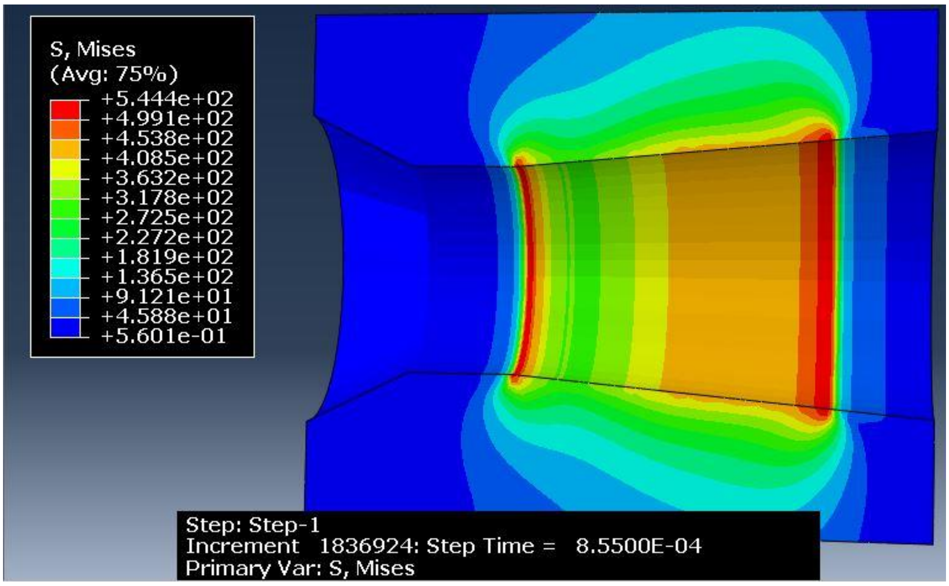
Fig. 5. Components of residual stress on drawn wire cross-section. α=5, coefficient of friction μ=0.05, Drawing speed

4. Results

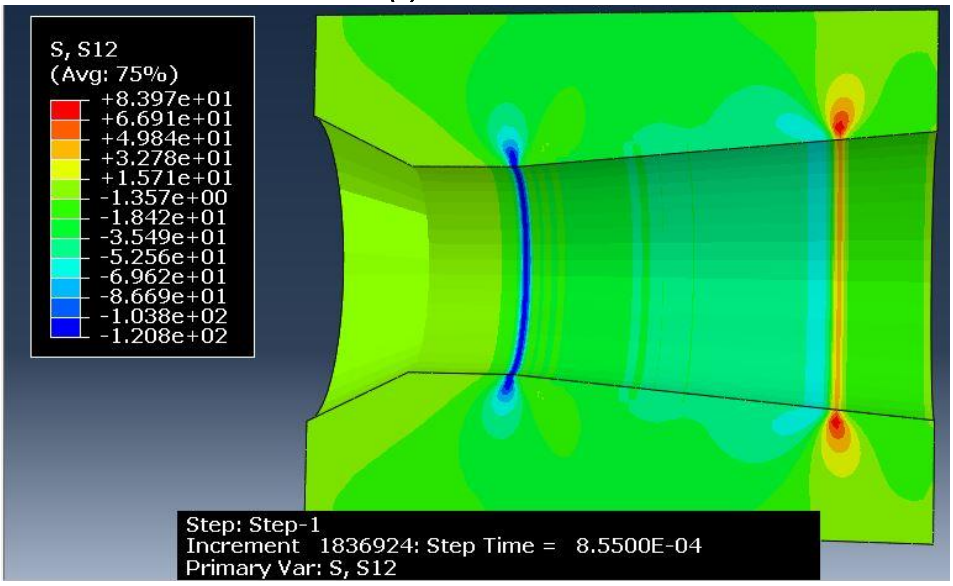
Data regarding the stress on the die surface, the strain on the wire section, temperature, and drawing force were gathered from FEM simulations. In this section, the trends in each diagram and the behavior of parameters concerning change in drawing angle and coefficient of friction have been described.

4.1 Stress distribution on die

Fig. 6 represents stress on the surface of the die in the deformation zone. According to Fig. 6, maximum misses and shear stress appear at the entrance and exit of the deformation zone on the die surface. These areas are where ringing wear appears on the die [9, 27-29].



(a)Misses stress



(b) Shear stress

Fig. 6. Stress on die cross-section. Semi-die angle α=10, coefficient of friction μ=0.05, Drawing speed v=1000 mm/s

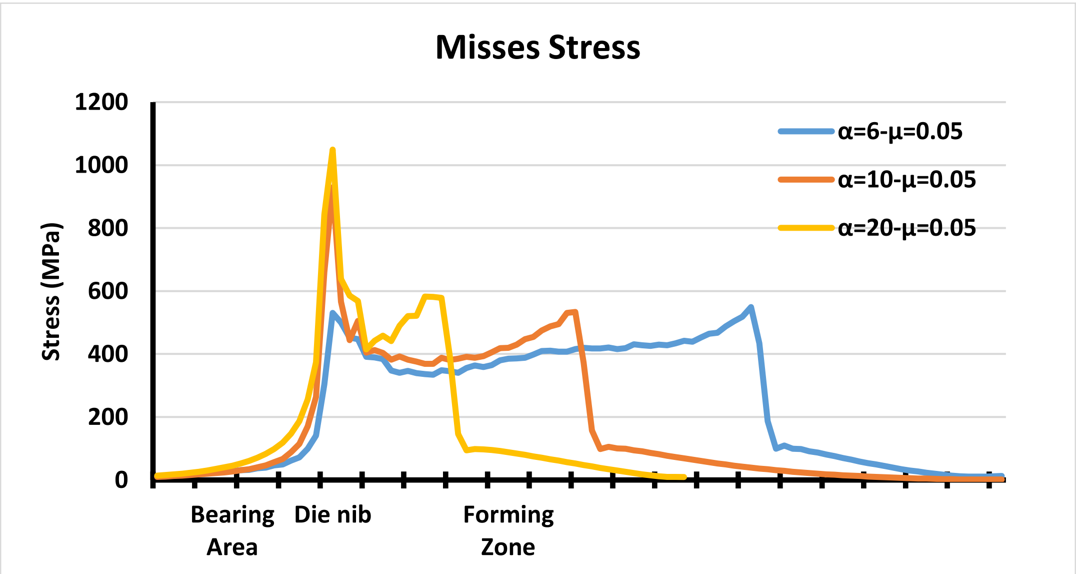


Fig. 7. Effect of drawing angle on misses stress distribution on die surface, coefficient of friction μ=0.05, Drawing speed v=1000 mm/s

Fig.7 depicts the distribution of Misses stresses on the die surface at different drawing angles. According to Fig.7, increasing the drawing angle shifts the profile of stress upward slightly but increases the peak of stress on the die nib considerably. Distribution of Misses stresses from the die entrance to exit, disregarding the drawing angle, is an upward curve that increases dramatically at the borders of the deformation zone (i.e., die entrance and die nib).

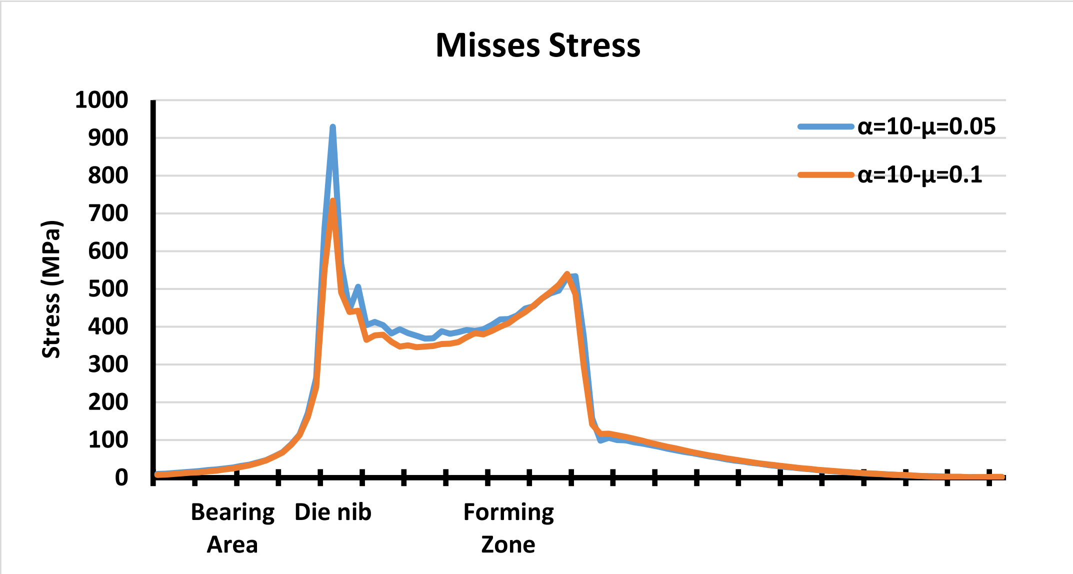


Fig. 8. Effect of coefficient of friction on misses stress distribution on the die surface, Semi-die angle α=10, Drawing speed v=1000 mm⁄s

Based on Fig. 8, increasing the coefficient of friction reduces the values of Misses stresses on the die surface in the deformation zone. The die entrance exhibits minimum sensitivity to friction changes but the Misses stress at the die nib and the area close to it decreases noticeably by increasing the coefficient of friction.

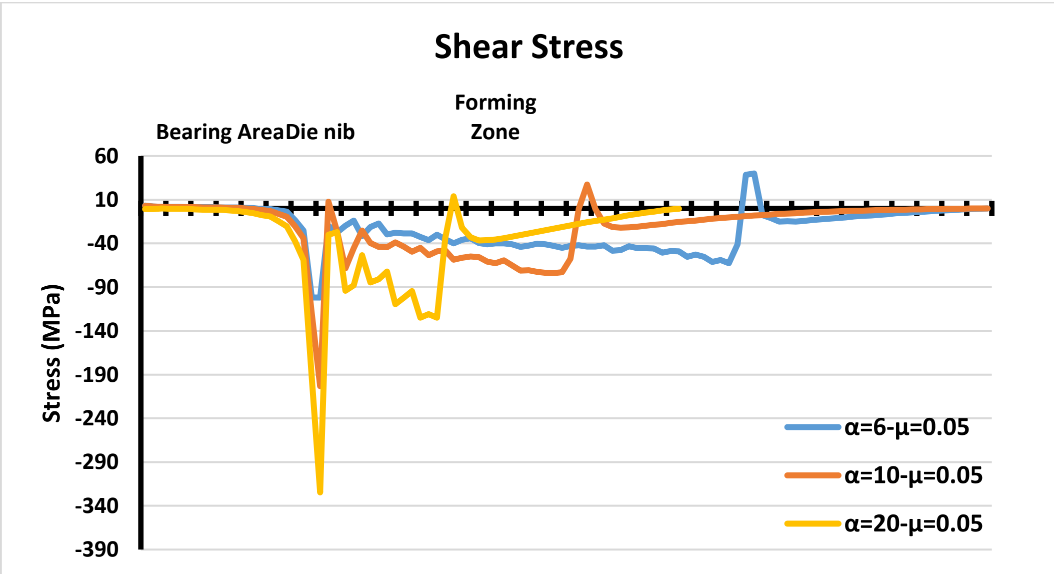


Fig. 9. Effect of drawing angle of shear stress distribution on the die surface, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s

Fig. 9 shows the changes in shear stress distribution on the die in terms of changes in the drawing angle. As represented in Fig. 9, increasing the drawing angle causes the absolute value of the shear stress profile to increase. Also, the amount of shear stress in the borders of the deformation zone increases by increasing the drawing angle.

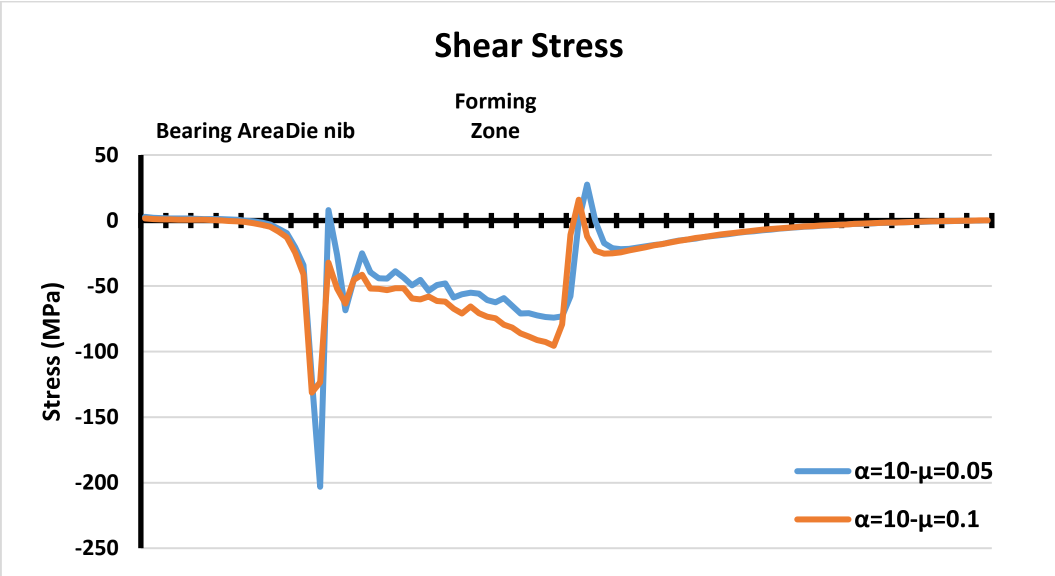


Fig. 10. Effect of the coefficient of friction on shear stress distribution on the die surface, Semi-die angle α=10, Drawing speed v=1000 mm⁄s

Fig. 10, shows the effect of change in the coefficient of friction on shear stress in the deformation zone. Increasing the coefficient of friction decreases the peak of shear stress on the die nib while it increases the shear stress in the deformation zone and the die entrance. To sum up, enhancement of drawing angle enhances both misses and shear stress. Increasing the coefficient of friction increases Misses and shear stress in the deformation zone but decreases them on the die nib. To improve the die stress condition, it is beneficial to draw the wire with a minimum semi-die angle and coefficient of friction.

4.2 Strain distribution

Fig. 11 shows the distribution of equal plastic strain in the drawn section. It is necessary to mention that a steady drawing area is created after a 0.4 mm drawing of wire in most cases in this study. Further simulation of the process does not change the distribution and amount of plastic strain and steady area after the deformation zone was chosen for measuring the profile of plastic strain in the wire section. According to Fig. 12, the plastic strain distribution is acceptable even in low semi-die angles. Drawing the wire with high semi-die angles disturbs this even distribution and creates a peak of strain near the surface but not at the surface of the wire. Change in the coefficient of friction had not a noticeable effect on the plastic strain distribution. Based on the distribution of equal plastic strain, it is better to draw wire at low angles to have even plastic distribution on the cross-section.

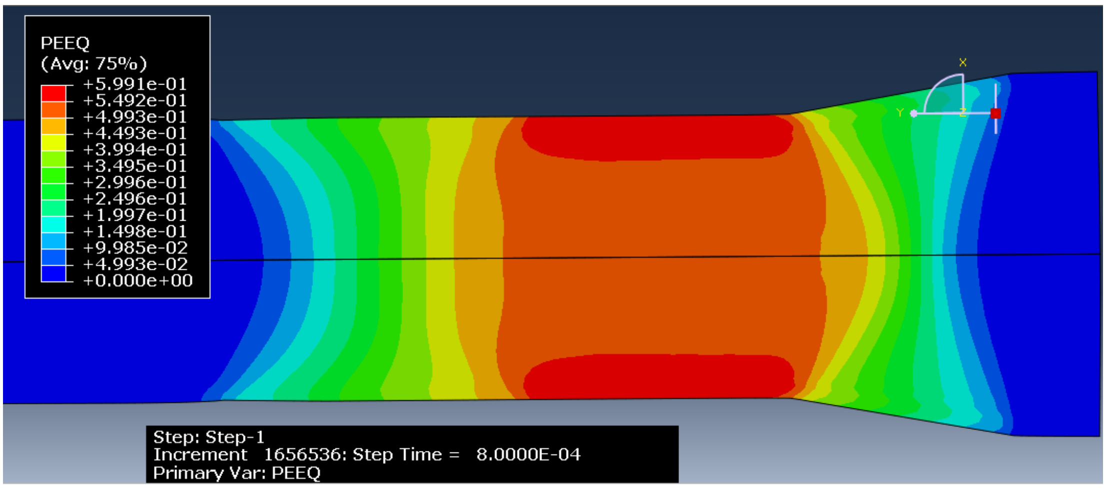


Fig. 11. Plastic equal strain (PEEQ) on wire cross section, Semi-die angle α=10, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s

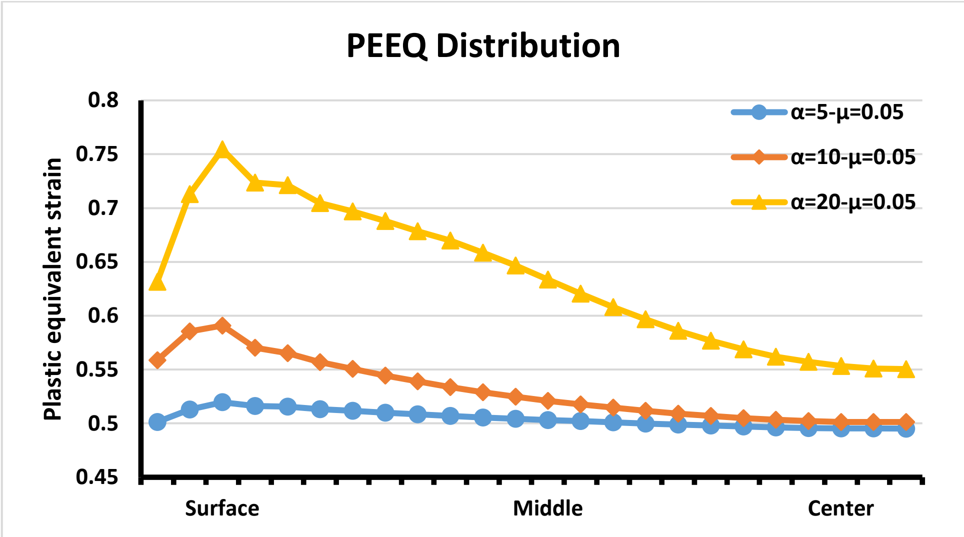
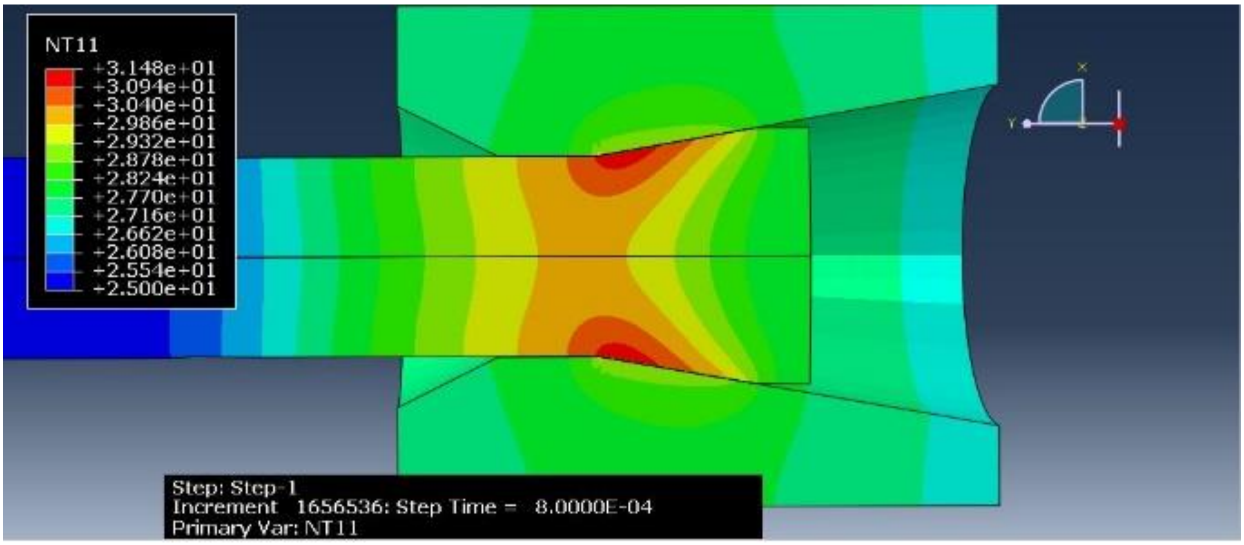


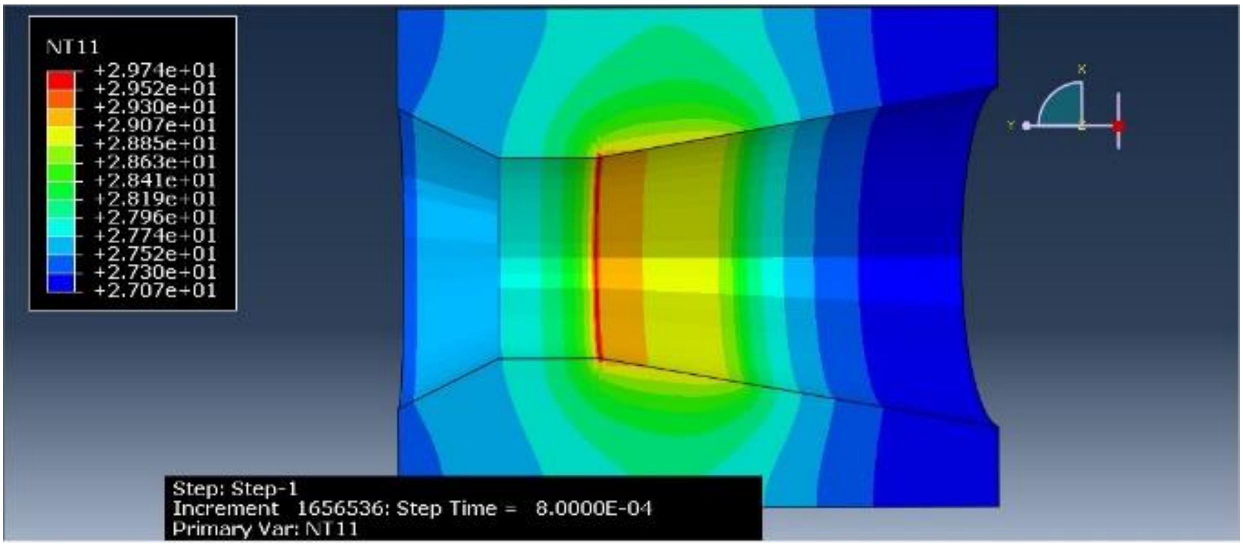
Fig. 12. Effect of drawing angle on Plastic equal strain (PEEQ) distribution on wire cross section after deformation

4.3 Temperature distribution

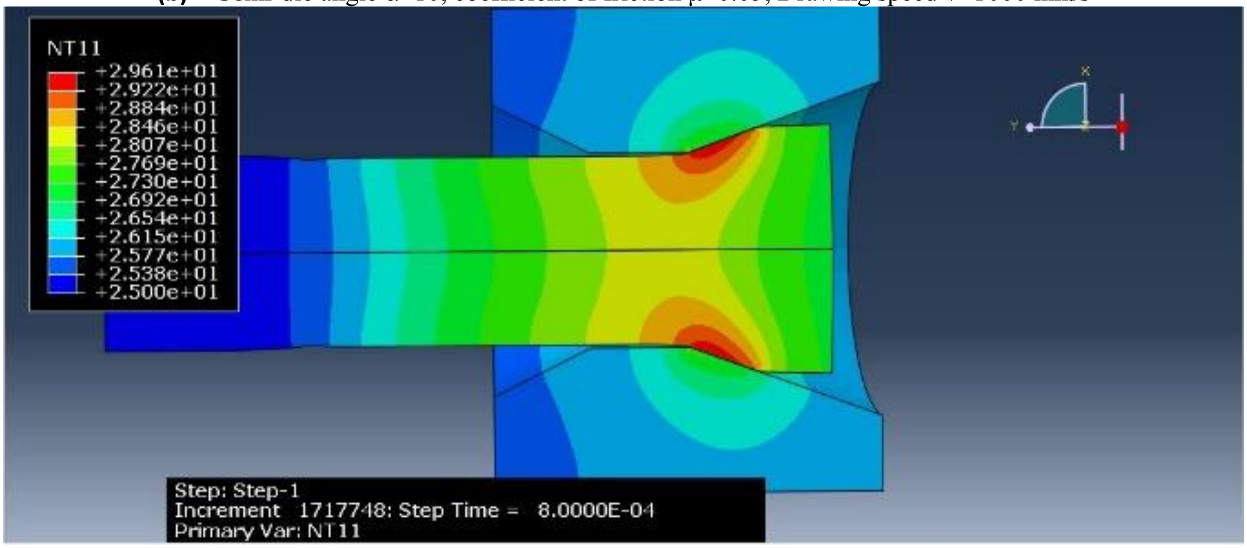
Fig.13 shows the temperature at the deformation zone on the die and wire. Needless to mention that by continuing the wire drawing, the temperature of the die increases steadily, but the temperature of the wire remains pretty fixed because every time new raw material at room temperature enters the deformation zone, and delivers a fraction of frictional energy to the die. The advantage of studying the drawing process of a unit of wire is that it gives us insight into the distribution of energy transferred to the die. According to Fig. 14, the maximum die temperature was observed on the die nib. Increasing the semi-die angle compacts the isothermal regions on the wire section and reduces the contact surface and temperature on the die surface. The described phenomenon is easier to observe with a higher coefficient of friction. Increasing the coefficient of friction increases the amount of the maximum temperature on the die and wire (Fig. 15 and Fig. 4). To have the lowest amount of temperature rise on the die and wire, it is better to draw the wire with a high semi-die angle and low coefficient of friction.



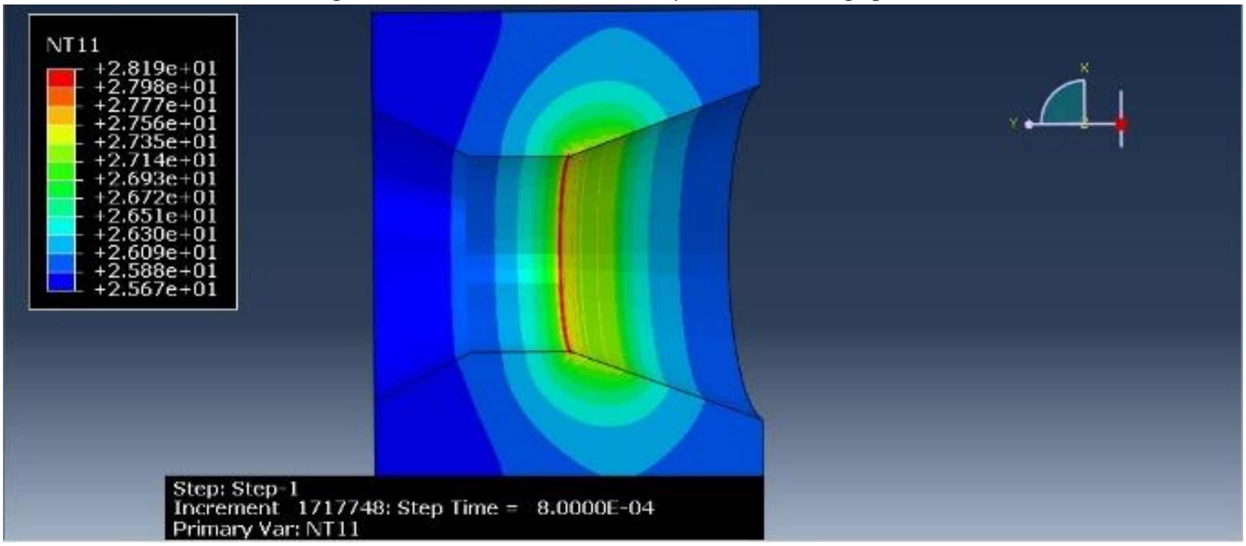
(a) Semi-die angle α=10, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s



(b) Semi-die angle α=10, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s



(c) Semi-die angle α=20, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s



(d) Semi-die angle α=20, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s

Fig. 13. Temperature on the die and wire.

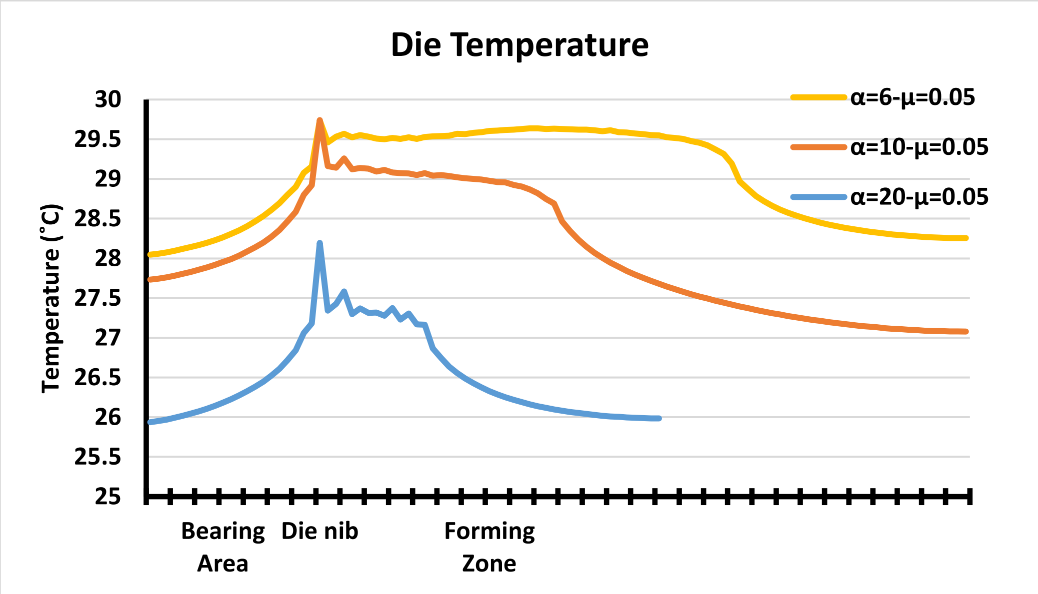


Fig. 14. Effect of drawing angle in temperature distribution on the die surface, coefficient of friction μ=0.05, Drawing speed v=1000 mm⁄s

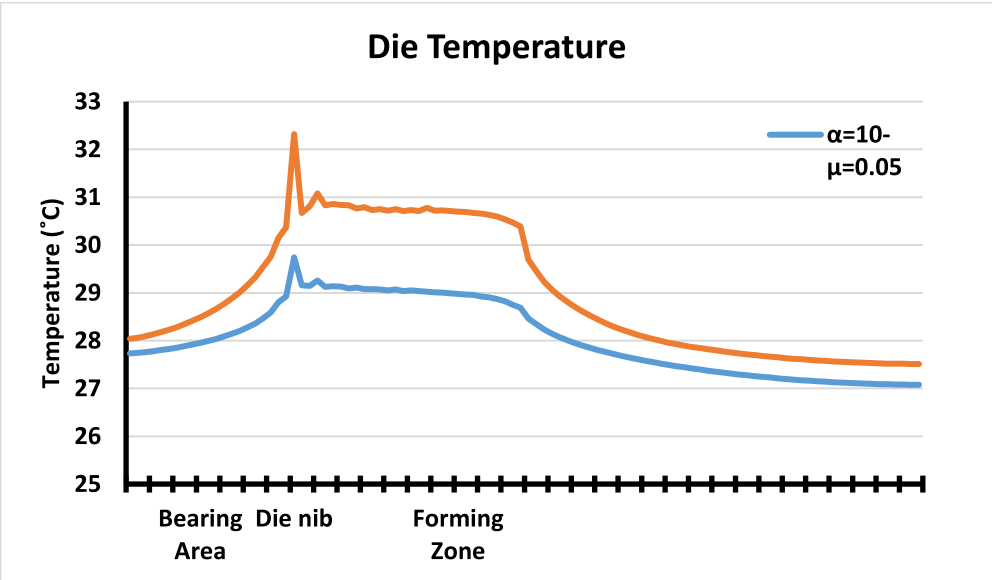


Fig. 15. Effect of the coefficient of friction on temperature distribution on die surface, semi-die angle α=10, Drawing speed v=1000 mm⁄s

4.4 Drawing force

Fig. 16 represents the drawing force in various die angles and coefficients of friction. Similar to the results of other researchers (Ref. [15]), this diagram has the lowest point between 7 to 10 degrees, where the amount of frictional and redundant work becomes minimized. Drawing the wire with an angle lower than 7 degrees increases frictional work while drawing it with an angle higher than ten increases redundant work. In both situations, the drawing force will be increased.

5. Discussion

Analyzing the data gathered in section 4 indicates that in wire drawing with its axisymmetric geometry, both components of stress on the die and distribution of strain on the wire are highly dependent on the semi-die angle. At a low semi-die angle, the area of the deformation zone increases and causes the wire to deform gradually to the final diameter. A large contact area in this situation results in an even distribution of Misses stress on the surface of the die but increases the drawing force and heat generated by friction. The distribution of strain in this condition is even and favorable on the wire section. A high semi-die angle disturbs the even distribution of stress on the surface of the die and increases the contribution of the die nib in forming process. It causes high misses to stress on the die nib, and maximum deformation induced on the wire on the last stage of deformation. The result is an uneven distribution of strain, and the maximum strain is close to the surface of the wire. On the other side, a high semi-die angle reduces the contact area between the die and wire and the resulting heat produced by friction.

The coefficient of friction has a complicated effect on the wire drawing. Increasing the coefficient of friction increases the shear stress on the surface of the die and wire as well. This situation assisted the process by increasing the deformation of wire in the deformation zone and alleviating stress on the die nib, but at the same time increasing the peak of shear stress on the die entrance. Increasing the coefficient of friction also increases the generated heat in the deformation zone. High temperature is detrimental to wire because of consequent chevron cracks and delamination.

The die entrance is the boundary between elastic and plastic wire material. Due to the axisymmetric geometry of the die, the material undergoes hydrostatic stress, and various semi-die angles have a low impact on the stress state in this location. This justifies the minimum sensitivity of Misses stress in die entrance related to the change in semi-die angle. On the other hand, increasing the coefficient of friction increases the fraction of shear stress on the die and wire surface and changes the state of stress on the material in the entrance. This can be the reason of sensitiveness of shear stress in die entrance to changes in the coefficient of friction.

Low drawing angle and coefficient of friction are beneficial in terms of even distribution of strain on the wire section and low-stress profile on the die surface. A high drawing angle is advantageous because of generating low heat in the deformation zone. Both groups of parameters meet on the optimum drawing force angle and the level of all of them is close to their optimum situation.

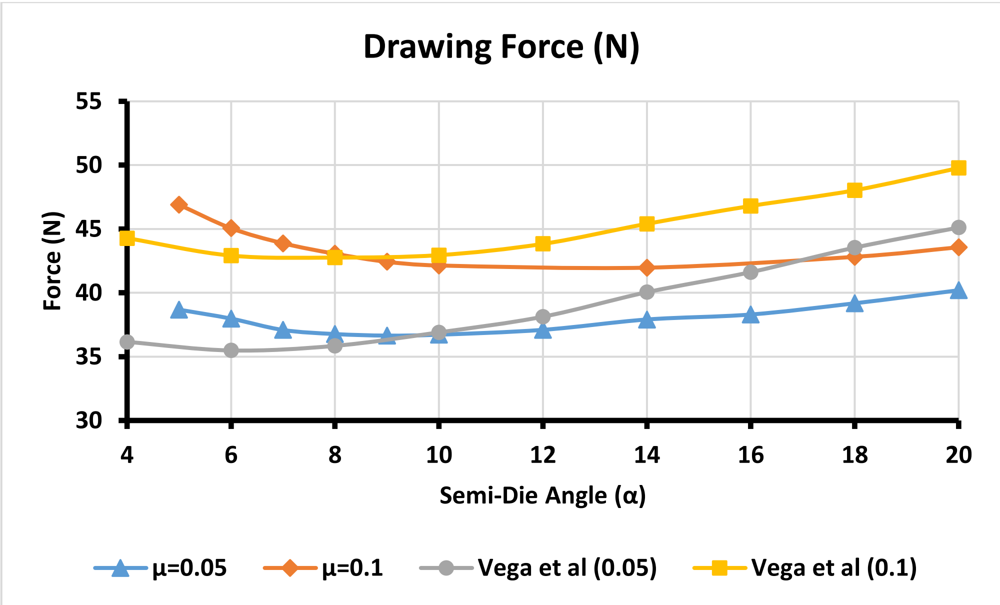


Fig. 16. Drawing force with different semi-die angles and coefficient of friction

6. Conclusion

In this study, the thermo-mechanical simulation of copper wire drawing with PCD die was conducted, and the following results were obtained:

1- Drawing with a high drawing angle diminishes the amount of temperature increase in wire and die.

2- The distribution of equal plastic strain is acceptable even at a low drawing angle.

3- Drawing with a low drawing angle lessens the stress profile and peaks of stress.

4- Drawing force minimized in a semi-die angle between 7 and 10 degrees. Although, at this point, the amount of temperature, the profile of stress, and the distribution of plastic strain are not in their best condition, but they are acceptably close to their optimum values.

5- The coefficient of friction has no noticeable effect on the plastic strain distribution of the wire section but exacerbates the temperature and shear stress profile on the die and increases the drawing force. Hence, it is beneficial to keep it as low as possible.

6- Peaks of misses and shear stress observed at the entrance and exit of the deformation zone. These areas are susceptible to ringing wear, as reported by other researchers.

7- The maximum amount of stress and temperature observed on the die nib. This area is the most sensitive point of conventional dies to wear

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