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Deformation behavior of 93 Tungsten alloy under hydrostatic extrusion

Babak Manafi[1,*] and Mehdi Saeidi[2]

[1]Department of Aerospace and Mechanical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.

[2]Young Researchers and Elites Club, Science and Research Branch, Islamic Azad University, Tehran, Iran.

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ABSTRACT

In this study, the deformation behavior of 93Tungsten alloy under the hydrostatic extrusion has been investigated. The hydrostatic extrusion process of 93 Tungsten alloy has been analyzed by means of finite element method (FEM). The numerical results were highly corresponded to the experimental ones. Also the effect of die angle on the extrusion pressure and applied damages to the 93 Tungsten alloy during the process of hydrostatic extrusion has been investigated according to the Cockcroft & Latham damage criterion. As was deduced from results, when the die angle has been considered as 30°, the applied damages to the material during the process were negligible in comparison with higher values of die angle.

Introduction

Nowadays, the extrusion process has an important place in the manufacturing industries [1]. In the hydrostatic extrusion, the billet has been subjected to uniform hydrostatic pressure. The billet has been surrounded by incompressible fluid that called pressure medium so the friction between the billet and container has been eliminated [2]. Also the friction between the die and the billet has been highly reduced due to the hydrodynamic lubrication film that has been formed between the billet and the die [3]. Eventually the extrusion pressure and the redundant deformation have been extremely reduced in comparison with forward extrusion [2].

At 70th, the hydrostatic extrusion process was studied extensively. Wilson and Walowit [4] founded the hydrodynamic lubrication theory for hydrostatic extrusion (in the case of axial symmetric deformation) according to the Reynolds equation. Hillier [5] and Kaujalgi [6] modeled the minimum thickness of the oil according to the minimum work technique in which the hydrodynamic effects of the input area (area of the beginning of deformation) was not calculated. The Hydrodynamic lubrication in the hydrostatic extrusion of the double reduction die has been investigated by Thiruvaradchelvan and Alexander [7]. They studied involved factors in the hydrodynamic lubrication phenomenon. Eventually the billet velocity, fluid properties, back pressure, and augmenting stress obtained as involved factors.

The evidences showed the lubrication at the first reduction was very good due to the presence of high pressure fluid and the lubrication at the second reduction was better than the simple die.

The hydrodynamic analysis on the hydrostatic extrusion of the tungsten alloy using the hydrodynamic lubrication theory and Reynolds equation has been carried out by Wang et al. [3]. The critical velocity equation has been obtained while the lubrication condition existed between the workpiece surface and die and also the relationship between the critical velocity and hydrostatic extrusion process parameters were discussed.

Eventually they established the theoretical foundation for the application of hydrostatic extrusion of the Tungsten alloy. Zhang and Wang [8] performed finite element analysis on the process of hydrostatic extrusion for 93 Tungsten alloy through the concave die with the equal-strain contour lines. They investigate the extrusion pressure and the distribution of strain and stress in the material during the process.

Eventually they exhibited the hydrostatic extrusion is an appropriate process for metals with high brittleness such as Tungsten alloys. Kopp and Barton [9] carried out the finite element analysis on the hydrostatic extrusion process of magnesium alloy.

Chen and You [10] used FEM to study the plastic deformation behavior of porous materials during the hydrostatic extrusion process. In their analyses, the die has been defined as a rigid body and the heat affects during the process have been ignored. The effect of the cone half angle (α), the initial density of porous billet, extrusion ratio, effective strain and stress, process force and the effect of the initial diameter of the billet on the damage have been investigated.

Tungsten heavy alloys exhibited a combination of high density, ductility, strength and toughness. They have been extensively used as kinetic energy penetrators, counterbalance weights and radiation shields [11]. The last researches [3, 8, 11] confirmed that the hydrostatic extrusion is suitable to process the hard-deformable metals. The hydrostatic extrusion has been well known as the best way to process Tungsten alloys as brittle metals.

Accordingly this study aimed to investigate the deformation behavior of 93 Tungsten alloy during the process of hydrostatic extrusion. In order to achieve applicable results, the numerical simulation results were highly corresponded to the experimental ones. Also the effect of die angle on the effective strain, effective stress and applied damage during the process has been investigated.

Tel: +989212784388
E-mail address: b.manafi@srbiau.ac.ir

Analysis of hydrostatic extrusion

Evaluating of the optimal forming pressure plays an important role in the die design for extrusion process [12, 13]. Based on the energy approach, below expression can be used for idealized extrusion pressure in forward extrusion process [2].

$$P = \bar{\sigma} \ln R \quad (1)$$

Where the $\bar{\sigma}$ is defined as the flow stress of applied material under compression. Hypothetically the above expression can well approximate the extrusion pressure in the process of hydrostatic extrusion due to negligible effect of friction in this process. It must be noted that the effects of friction and redundant deformation have not been considered in this expression but as was mentioned earlier, in the process of hydrostatic extrusion the friction is very negligible and so it is possible to use die with very small semicone angle which extremely reduced the redundant deformation in this process. DePierre obtained the total extrusion force is the sum of die force and friction force. But in the hydrostatic extrusion the effects of friction can be ignored so even only the die force can well predict the total extrusion force. The expression for extrusion pressure by means of energy approach with consideration of redundant deformation has been obtained as follows [2].

$$p_d = \sigma_0 (a + b \ln R) \quad (2)$$

Where a and b were 0.8 and 1.5 respectively for axisymmetric extrusion. Avitzur [2] established a more generalized expression according to a spherical velocity field. This expression can be used for lubricated extrusion through a die of semiangle α.

$$p_d = \frac{2\sigma_0}{\sqrt{3}}\left(\frac{\alpha}{\sin^2\alpha} - \cot\alpha\right) + \sigma_0[2f(\alpha) + m\cot\alpha]\ln(\frac{r_0}{r_f}) + 2m\left[\frac{L}{r_0} - \left(1 - \frac{r_f}{r_0}\right)\cot\alpha\right] \quad (3)$$

Where m, f(α), α, L, r_0, r_f were interfacial friction factor, complex function of semidie angle, semidie angle, the length of land on exit from die, radius of billet and radius of extruded rod respectively. For small semidie angle, f (α) =1. In the Avitzur expression, the effects of die angle have been considered. But the capability of Avitzur expression in predicting the pressure in the hydrostatic extrusion must be investigated. Recently the Equi-Potential Lines Method has been applied to estimate the pressure in extrusion process [12].

Ductile damage criteria

Ductile fracture can be described as a fracture that occurs after a component experiences a significant amount of plastic deformation. Fracture has been affected by various parameters comprised of deformation history of material during the process and the process parameters such as rate of deformation, lubrication and friction. The other factors that influence fracture include chemical composition, microstructure, surface conditions, and homogeneity. There are several ductile fracture criteria that have been used to predict the surface or internal cracks. All of them can be generally represented by [14]:

$$\int F(deformation)d\varepsilon = C \quad (4)$$

The expression (4) indicates that the ductile fracture is a function of the plastic deformation history and material properties. When the maximum damage value (MDV) of the material rises above the critical damage value (CDV), crack formation is anticipated. Different ductile fracture criteria yield different damage values for a given process [14]. Some ductile damage criteria have been represented as follows:

$$\int_0^{\varepsilon_R}\left(1 + A\frac{\sigma_H}{\sigma_{eq}}\right) d\varepsilon_{eq} \geq C \quad (5)$$

Where A is a constant, C is the critical damage value, σ_H is the hydrostatic stress, σ_{eq} is the equivalent stress and ε_{eq} is the equivalent strain. The theory of this criterion is based on that in the metal forming processes; the fracture was modeled as void initiation and growth, followed by coalescence to form a crack. This criterion has been proposed by McClintock and Oyane [15].

$$\int_0^{\varepsilon_R}\left(\frac{\sigma_H}{\sigma_{eq}}\right) d\varepsilon_{eq} \geq C \quad (6)$$

In which the C is the critical damage value. This criterion (equation (6)) is known as Ayada damage criterion [15].

$$\int_0^{\varepsilon_R}(\sigma_1\dot{\varepsilon}_1 + \sigma_2\dot{\varepsilon}_2 + \sigma_3\dot{\varepsilon}_3) \geq C \quad (7)$$

Where C is the critical damage value.σ1, σ2 and σ3 are the principle stresses and $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ and $\dot{\varepsilon}_3$ are the corresponding principle strain rates. This criterion (equation (7)) is known as Generalized work (GW) criterion or Freudenthal criterion [15].

$$\int_0^{\bar{\varepsilon}_f}\frac{\sigma_{max}}{\bar{\sigma}}d\bar{\varepsilon} \geq C \quad (8)$$

Where the σ_{max}, σ, $\bar{\varepsilon}$, $\bar{\varepsilon}_f$ and C are the maximum principal stress, equivalent stress, equivalent stain, equivalent fracture strain and critical damage value respectively. This criterion (equation (8)) is known as Cockcroft & Latham damage model [15-18]. According to this criterion, the fracture is occurred when the damage reaches to the critical value. The DEFORM software has the capability of calculating the probability of failure based on this criterion by means of FEM.

FEM procedure

The finite element simulation of hydrostatic extrusion of 93 Tungsten alloy has been performed and its results compared with experimental ones [8]. The diameter of billet was 20 mm. the amount of deformation in all experiments has been set as 50 %. The die angle has been changed in order to investigate the effect of die angle on the deformation behavior of 93 Tungsten alloy under the hydrostatic extrusion. The investigated values of die angle comprised of 30°, 45° and 60°. The material properties of 93 Tungsten alloy has been shown in the Table 1 [8].

Table 1. The material properties of 93Tungsten alloy.

Material	Density (g/cm^3)	Poisson ratio	Elastic modulus (GPa)	Yield stress (Mpa)	Strain hardening exponent
93 Tungsten alloy	17.6	0.29	360	920	0.05

The flow curve of 93 Tungsten alloy can be expressed as follows:

$$\sigma = 1374 \times \varepsilon^{0.05} \quad (9)$$

The stress-strain curve for this alloy based on the above expression has been plotted in the Fig. 1.

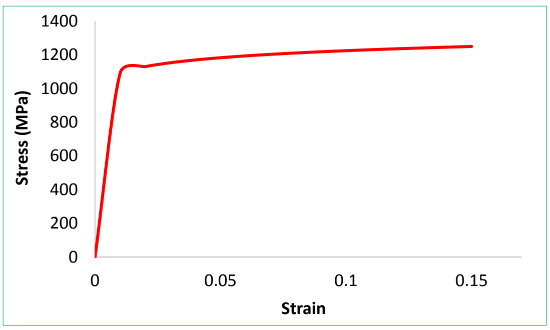

Figure 1. The stress-strain curve of 93 Tungsten alloy.

The DEFORM 3D Ver. 6.1 has been used for finite element simulation. The die has been considered as a rigid body due to its insignificant elastic deformation during the process. The billet has been defined as elastic-plastic material so the strain-hardening effect has been considered. The element type was tetrahedral. The mesh sensitivity test has been performed and suitable mesh number obtained as 27000. The pressure boundary condition has been defined around the billet instead of the medium pressure. The friction type considered as shear. Because of the nature of the process, the hydrodynamic lubrication has been occurred in die so the friction factor must be selected as 0.05 in this area due to this fact [8, 10, 19]. The type of simulation was Lagrangian Incremental. The iteration method selected as direct. The convergence error limit for velocity and force were 0.005 and 0.05 respectively. The global remeshing was chosen and the type of interference depth selected as relative and its value considered as 0.7. The Conjugate-Gradient solver has been used to solve the problem.

Results and discussions

The performed experiments [8] on the hydrostatic extrusion of 93 Tungsten alloy have been analyzed by FEM and the results have been reported in the Table 2.

As was shown in the Table 2, the maximum error between results of finite element simulation and experiments has been obtained as 5 %. So the FEM simulations well approximate the extrusion pressure in the process of hydrostatic extrusion. By placing the yield strength of 93 Tungsten alloy and extrusion ratio in the equations (1, 2, and 3), the extrusion pressure for these three conditions have been obtained and were reported in the Table 3. It must be noted that for applying the hydrostatic extrusion condition, the friction factor has been considered as zero in the Avitzur expression (equation (3)).

As was obtained from Table 2 and Table 3, the equation (1) better approximate the extrusion pressure in the hydrostatic extrusion process with regard to this fact that it calculated the same value for different die angles. The equation (2) has very large error on the extrusion pressure because the redundant deformation is very negligible in the process of hydrostatic extrusion. The results confirmed that the Avitzur expression (equation (3)) has not been suitable to calculate the extrusion pressure for hydrostatic extrusion even by considering the friction factor as zero.

As was mentioned earlier, the Amount of deformation was 50 % in all simulations due to investigate the effect of die angle on the extrusion pressure. In the simple forward extrusion [20], the extrusion pressure has been increased by elevating the die angle. But as was obtained by both experiments and simulations, in the hydrostatic extrusion, the extrusion pressure changes very low by altering the die angle because the friction between the die and billet during the process is negligible due to the hydrodynamic lubrication phenomenon. So by increasing the die angle the extrusion pressure changes very low when the die angle was less than 45°. By changing the die angle from 30° to the 45°, the extrusion pressure just changes about 15 MPa in the experiments, this fact is obvious in the Table 2. But when the die angle considered as 60°, the extrusion pressure increased about 125 MPa than its value at die angle of 30°.

The distributions of effective stress for Exp. 1 and Exp. 3 conditions have been shown in the Fig. 2(a), 2(b) respectively.

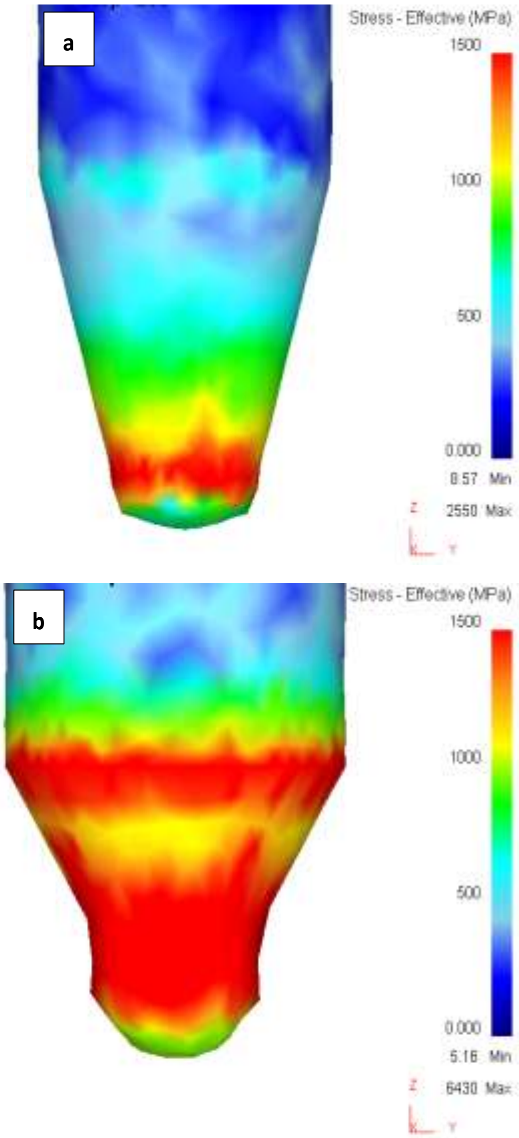

Figure 2. Distribution of effective stress at a) Exp. 1 b) Exp. 3

As was shown in the Fig. 2, the effective stress has been increased by elevating the die angle in the process of hydrostatic extrusion. The maximum effective stress at Exp. 3 condition in which the die angle was 60° obtained about three times more than that in the Exp. 1 condition. The distributions of effective strain at Exp. 1, Exp. 2 and Exp. 3 conditions have been shown in the Fig. 3(a), 3(b) and 3(c) respectively. It is obvious that the amount of effective strain has been increased by elevating the die angle. As was shown in the Fig. 3, the amount of effective strain at die angle of 30° was very lower than that in the die angle of 60°. The maximum effective strain at die angles of 30°, 45° and 60° were obtained as 0.705, 1.12 and 2.35 respectively.

Table 2. Comparison of the numerical pressure and experimental results

Experiment No.	Amount of deformation (%)	Die angle (2α)	Numerical simulation pressure (MPa)	Experimental pressure (MPa)	Error (%)
1	50	30°	974	1005	3
2	50	45°	955	990	3.5
3	50	60°	1073	1130	5

Table 3. The results of theoretical pressure.

Experiment No.	Amount of deformation (%)	Die angle (2α)	Theoretical pressure based on equation (1)	Theoretical pressure based on equation (2)	Theoretical pressure based on equation (3)
1	50	30°	1275.39	2649	1465.54
2	50	45°	1275.39	2649	1568.38
3	50	60°	1275.39	2649	1637

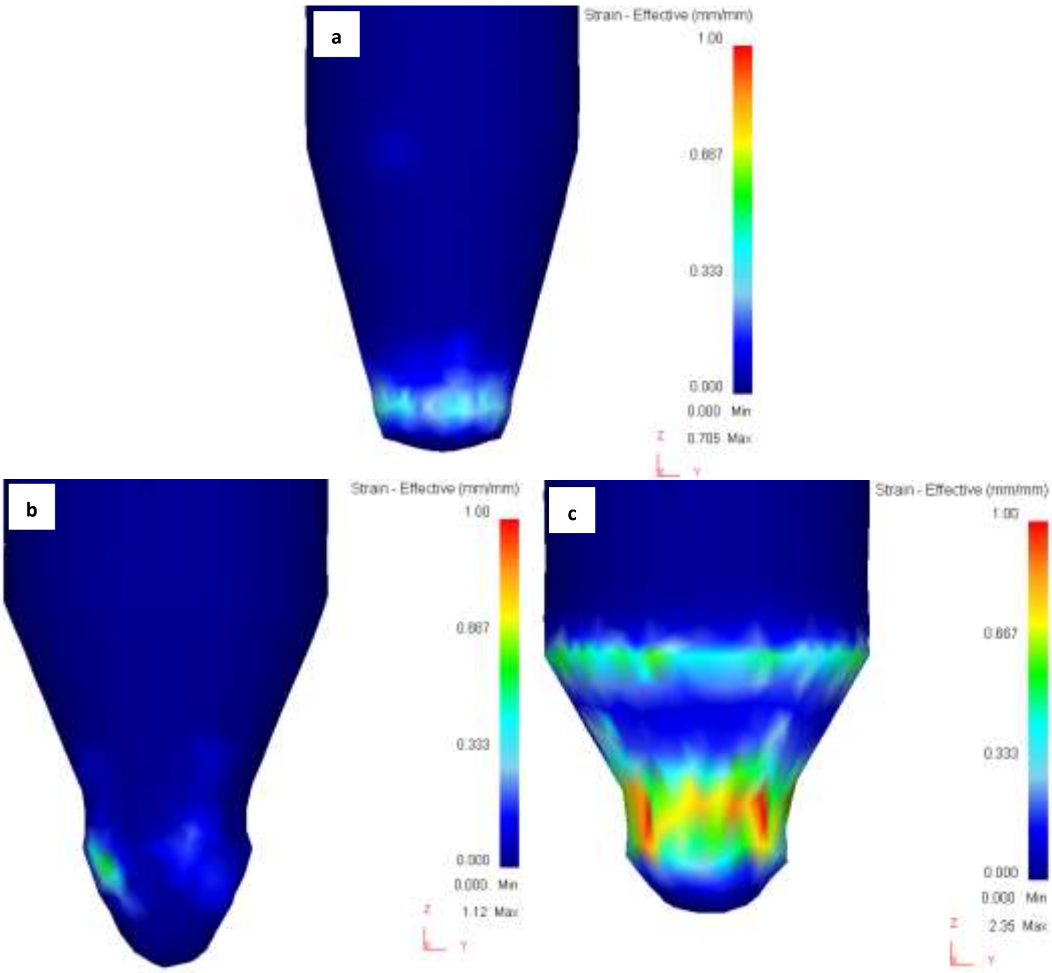

Figure 3. Distribution of effective strain at a) Exp. 1 b) Exp. 2 c) Exp. 3.

The level of hydrostatic extrusion plays an important role in achieving a successful forming operation without fracture. The tensile stress below the critical value is decreased due to the presence of high hydrostatic pressure, while at the same time the flow stress is uninfluenced. Also when a deformation was performed under high hydrostatic pressure, it applies less damages to the under process material [2].

Obviously by regarding to all of these benefits, the hydrostatic extrusion is the best option to form a material without fracture. For investigating this fact, the Deform software has been used to calculate the probability of ductile fracture in the hydrostatic extrusion of 93 Tungsten alloy according to the Cockcroft & Latham damage criterion. The contours of damage value based on the Cockcroft & Latham criterion for Exp. 1, Exp. 2 and Exp. 3 conditions have been shown in the Fig. 4(a), 4(b) and 4(c) respectively.

As was shown in the Fig. 4, the damage value is increased with raising the die angle. So the probability of surface crack in 93 Tungsten alloy when it has been extrude by this process has been increased by elevating the die angle. The damage value is very negligible when the die angle considered as 30°. As was mentioned earlier, the hydrostatic extrusion has the capability of using die with smaller semidie angle (about 20°). So in the hydrostatic extrusion it is possible to use smaller semidie angle to produce products [2].

This makes the hydrostatic extrusion process useful to produce without fracture products from brittleness materials. The maximum damage value at die angles of 30°, 45° and 60° obtained as 0.0693, 0.325 and 0.613 respectively. The results confirmed that the damage value highly affected by the die angle.

The maximum damage value at die angle of 60° is about ten times more than that at die angle of 30°. This shows that it is better to keep the die angle about 30° in the process of hydrostatic extrusion of 93 Tungsten alloy by regarding to this fact that even by setting low semidie angle in this process, the extrusion pressure has not been increased due to the lack of friction and also the redundant deformation has not been took place in the small die angles.

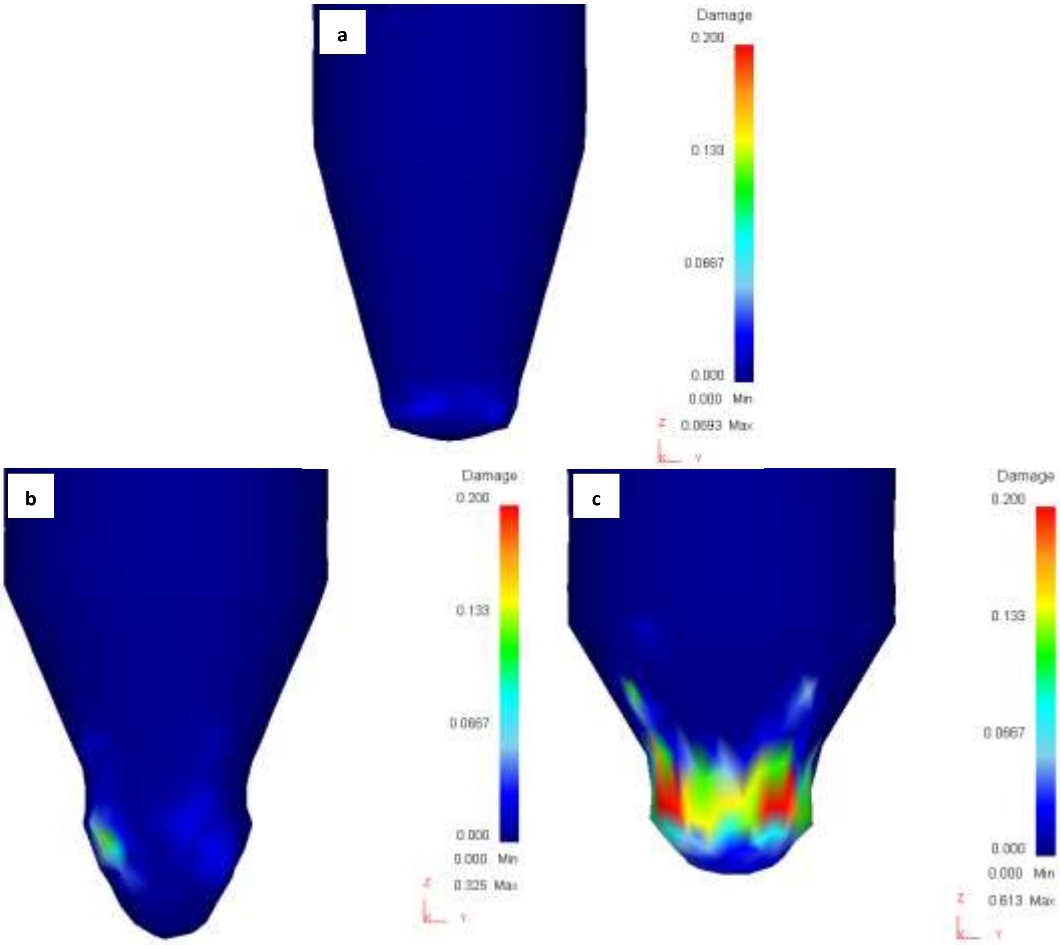

Figure 4. Distribution of damage value at a) Exp. 1 b) Exp. 2 c) Exp. 3

Conclusions

This study aimed to investigate the deformation behavior and applied damages to the 93 Tungsten alloy under hydrostatic extrusion. In order to achieve applicable results the numerical results were validated by means of experiments. According to the obtained results, the die angle has little impact on the extrusion pressure due to the negligible friction in the die during this process. The hydrodynamic lubrication phenomenon extremely reduces the friction in the die so the die angle has negligible impact on the extrusion pressure in this process. By comparing the theoretical expressions on the extrusion pressure with experimental results, the redundant deformation has been obtained very negligible in this process. The damage value based on the Cockcroft & Latham criterion confirmed that the probability of failure in the processed material under hydrostatic extrusion has been increased by raising the die angle. When the die angle has been selected as 30°, the applied damage to the processed material was very small so by regarding to the benefits of hydrodynamic lubrication in the hydrostatic extrusion process, it is highly recommended to use die with die angle below the 45°.

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