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Numerical study of the effects of process parameters on tool life in a cold radial forging process

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Abstract. Radial forging is an open die forging process used for reducing the diameters of shafts, tubes, stepped shafts and axles, and for creating internal profiles in tubes. Due to very large forging loads, the tool should withstand high stress and wear. Therefore, the success of the forging process depends upon recognition of the die failure factors and optimization of the tool working conditions that enhance tool life. In this study, the effect of process parameters on tool life in the cold radial forging process is investigated using nonlinear three dimensional finite element modeling. Wear and mechanical fatigue are considered as the main modes of tool failure, and a parametric study on the effect of process parameters on tool life is presented.

1. Introduction

Radial forging is a hot or cold forging process in which two or four hammers (dies) with radial strokes are utilized for forging solid or tubular components. This process is usually used for reducing the diameter of ingots and bars, the forging of stepped shafts and axles, and the production of tubular components with and without internal profiles, such as rifle barrels [1]. Deformation in radial forging results from a large number of short cycle, high speed hammer impacts on the workpiece. The workpiece has both rotational and axial feed between the strokes, and dies are arranged circumferentially around the workpiece, as shown in Figure 1 [2,3].

The Radial Forging (RF) process has been investigated by many researchers in the past. Lahoti et al. [4] and Lahoti and Altan [2] analyzed the mechanics of RF for single and compound angle dies using a slab method. In another study, Lahoti et al. [5] studied the effects of die design parameters on deformation in the RF. Using a modular upper bound technique, Subramanian et al. [6] modeled metal flow in a die cavity during the rifling of gun barrels under plane strain condition. Ghaei et al. [3] studied the effects of die shape in RF using slab method analysis. In another work, they used an upper bound method to estimate the maximum required forging load in RF [7]. In more recent work, the finite element method has been used to model and predict the RF process. Tszeng and Kobayashi [8] were the first to model the process of tube forging using the FEM. Domblesky et al. [9] presented a finite element model to determine the strain, strain rate, and temperature distribution in radial forging. Jang and Liou [10] also used FEM to evaluate the residual stresses in RF. Ghaei and Movahhedy [11] used a full 3D FEM simulation to model the radial forging process and investigated the effects of die cross-section on tube deformation. In another study, they [3] used FEM to study the radial forging of tubes without a mandrel and compared the predicted forging load with available experimental data.

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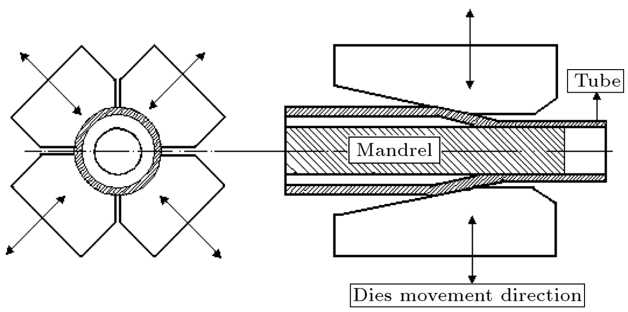

Figure 1. Arrangement of radial forging dies.

The forging loads are usually very high. The die should withstand high stress and tool life is a determining factor. Therefore, it is essential to recognize the failure modes and to optimize the working conditions of the tool to enhance tool life and achieve high productivity. The failure of a tool slows production, increases rejected parts, and requires new adjustment to the machine. Often, in practice, the lifetime of the tool is not optimized, which means a loss of around 10% of the cost of the finished part [12]. Excessive die wear and cracks due to fatigue are common modes of die failure in radial forging applications. According to an investigation about die life, as much as 70% of the tools have to be replaced because of wear. Another 25% are due to mechanical fatigue, and the remaining 5% are due to plastic deformation and thermal-mechanical fatigue [13,14].

Tool life and tool failure in various cold, warm and hot forging processes have been extensively studied in the literature [12,13,15-19]. This study focuses on tool life in the radial forging process and is aimed at investigation of the effects of various process parameters on die life in this process. A nonlinear three dimensional finite element model of radial forging is developed. The die is modeled as deformable bodies, and a stress based criterion for tool failure is presented. The dissipated energy and the maximum Von-Mises stress in the die are used for the prediction of wear and mechanical fatigue, respectively. The effects of die geometrical features and process parameters, such as feed rates and frictional conditions, on tool failure are investigated.

2. Modeling procedure

A three dimensional model is developed for simulation of the radial forging of tubes using the ABAQUS/Standard commercial FE code. First order brick elements with reduced integration and hourglass control are used to mesh the tube. Since the die and the mandrel undergo very little deflection compared to the deforming tube, it is common to model them as rigid bodies [3,11]. However, to study die life, the stresses developed in the die are needed, and, therefore, in the current study, the die is modeled as a deformable body. The mandrel is modeled using 3D rigid 4-node elements. Due to the symmetry of the process geometry, it is sufficient to model only one eighth of a mandrel and half of a hammer (die) to reduce computational time.

It is assumed that the process is performed under isothermal conditions. The simulated tube is made of AISI 1015. A power law constitutive law, in the form of $\sigma = k\varepsilon^n$, is used [1], where k and n values at room temperature are given as $k = 618.14$MPa and $n = 0.1184$. The die material is cold worked tool steel material (AISI D2) with an initial yield stress of 1600 MPa. The elastic modulus and Poisson ratio for both tube and die materials are 210 MPa and 0.3, respectively. The frictional contact between contacting surfaces is implemented using a penalty method. In order to obtain the limiting shear stress, a check-run analysis was performed initially, assuming frictionless contact surfaces, and the maximum Von-Mises was found to be around 420 MPa in the workpiece. The limiting shear stress was set equal to $\bar{\sigma}/\sqrt{3} = 420/\sqrt{3} =$ 240 MPa in subsequent analyses. Also, the Coulomb friction coefficient was set to be 0.2. Figure 2 shows the configuration of the die, tube and mandrel in the simulation.

A schematic view of a typical radial forging die is shown in Figure 3. The most important features to influence process outcome are the conical inlet, the cylindrical section and the transverse angle.

A longitudinal section of the radial forging die

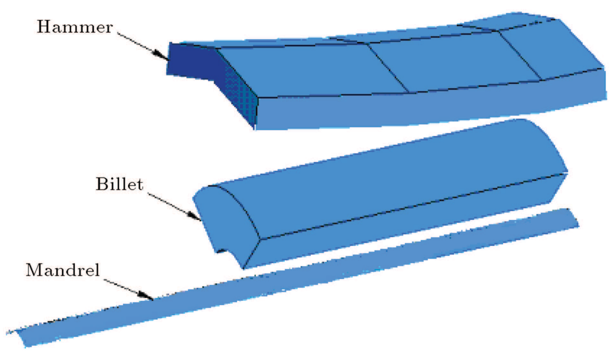

Figure 2. Configuration of the die, tube and mandrel.

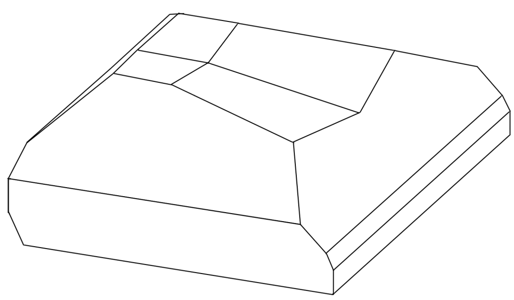

Figure 3. Schematic of a radial forging die.

is shown in Figure 4. The inlet angle, which is the angle of the conical inlet (α) and the land length of the cylindrical part (b), are shown in this figure. The transverse section of the die is shown in Figure 5, on which the transverse angle (γ) is demonstrated.

The tube, die and mandrel geometries are described in Tables 1 to 3, respectively. Note that some of the die parameters are simulated with a range of values to study their effect on the process parameters.

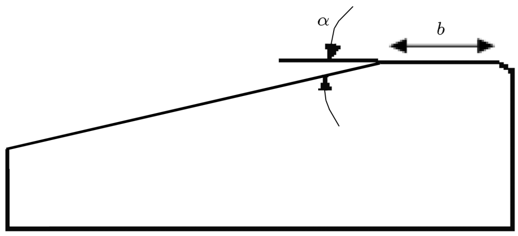

Figure 4. Longitudinal section of die, showing inlet angle (α) and land length (b).

Figure 5. Transverse section of die, showing transverse angle (γ).

Table 1. Initial and final tube geometry.

Outer radius of preform	O.D.	15.5 mm
Inner radius of preform	I.D.	5.8 mm
Length of the preform	L_0	312 mm
Outer radius of forged product	o.d.	12 mm
Inner radius of forged product	i.d.	3.915 mm
Length of the forged product	L_f	490 mm
Percentage of reduction in area	Red	38%

Table 2. Die geometry.

Die inlet angle	α	4 to 10°
Die transverse angle	γ	135 to 165°
Die land length	L_{LAND}	2 to 20 mm
Length of die inlet	L_I	21 mm
Total length of die	L_{DIE}	70 mm
Total depth of die	H_{DIE}	37 mm

Table 3. Mandrel geometry.

Radius of mandrel	R_M	3.915
Effective length of mandrel	L_M	40 mm
Angle of tapered head	γ	15°
Length of tapered head	$L_{T.H}$	3.7 mm

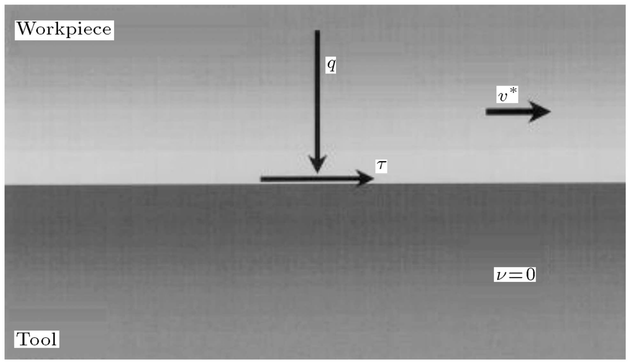

Figure 6. Diagram showing the conditions on the tool/workpiece interface [13].

3. Wear analysis

Wear is the progressive loss of material from the operating surface of a body caused by relative motion at its interface with another surface [20,21]. Many models have been developed for estimation of the wear amount at contacting interfaces. Most wear models correlate wear volume with physical quantities, such as load, sliding distance, coefficient of friction, and hardness, etc. The wear criterion used in this paper is the dissipated energy model, which assumes that the amount of wear is dependent on the dissipated energy at the tool/workpiece interface. According to this model, the worn-off material, V, is proportional to the dissipated energy per area, w, when the material slides a distance, l, along a tool surface under the influence of shear stress, τ, as shown in Figure 6 [13,14,20,21]. This function is given as:

$$V = k \cdot w = k \cdot \tau \cdot l. \tag{1}$$

The coefficient, k, is called the specific wear rate, and is calculated from the following equation:

$$k = \frac{K}{H}, \tag{2}$$

in which H is the ratio between the hardness of the workpiece and the tool, and the wear coefficient, K, is the coefficient of proportionality used as a measure of the material wear behavior.

The contact shear stress and the sliding length at the die/workpiece interface are obtained for all interface nodes from the FE simulation. In addition, the maximum Von-Mises stress on the die/workpiece interface is used as the measure of die stress in each case.

4. The effects of die geometry and process parameters on die life

The effects of die geometrical features and workpiece rotational feed rate on tool failure are investigated separately in the following paragraphs.

4.1. Die inlet angle

Figure 7 shows the sliding length at the die/workpiece interface and the shear stress on this surface under different die inlet angles. The axial feed and other parameters are kept constant for all cases. The figure shows that when this angle increases, the shear stress, mainly due to friction, does not vary significantly. However, the sliding length decreases with an increase in inlet angle. As the die inlet angle increases, the area of the contact surface between the die and the workpiece decreases, and the workpiece material travels a smaller distance on the die surface, which reduces the sliding length. This leads to a decrease in wear for larger die inlet angle, as shown in Figure 8.

Figure 9 shows the forging force and maximum Von-Mises stress on the die for different die inlet angles. As the die inlet angle increases, a smaller portion of the workpiece is deformed in each die stroke, which leads to the reduction of the force and Von-Mises stress, as shown in Figure 9. This is consistent with the prediction of less wear at higher inlet angles.

It is, thus, observed that increasing die inlet angle decreases both wear and maximum stress in the die. Consequently, a larger die inlet angle is preferred for increasing die life in the radial forging process. It should be noted, however, that a larger die inlet angle reduces penetration of the plastic deformation in the depth of the workpiece, and lowers the uniformity of deformation in the forged product.

Further examination of simulation results shows that maximum stress occurs at the middle of the die conical inlet, where the die/workpiece contact begins and deformation is maximum, as well as at the end of the die cone near the cylindrical part, where the work hardened material is deforming. Sample contour plots of the Von-Mises stress on the die inner and outer surfaces are shown in Figures 10 and 11.

Figures 12 and 13 show the contour plots of the contact shear stress and the contact sliding length at the interface, respectively. It is observed that the maximum values of both parameters occur at parts of the workpiece that are in contact with the end of the die cone near the cylindrical part. Therefore, the

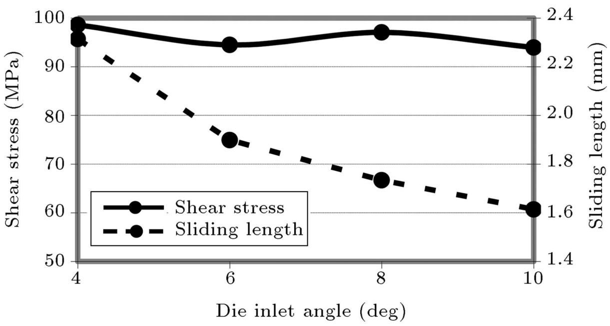

Figure 7. Shear stress and sliding length on the die/workpiece interface.

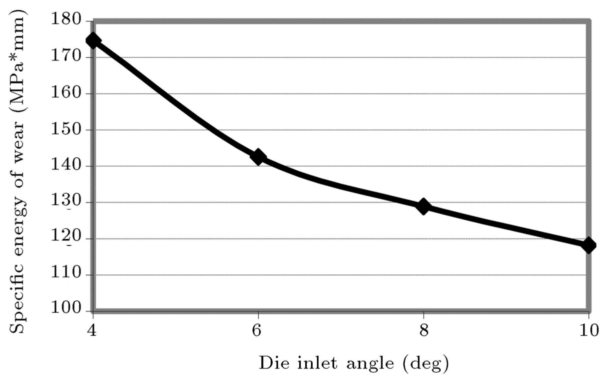

Figure 8. Effect of die inlet angle on the die wear.

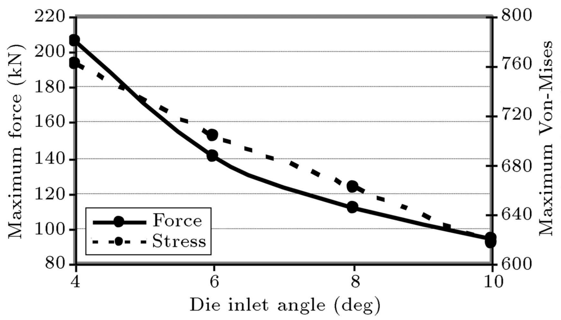

Figure 9. Effect of die inlet angle on the force and stress created in the die.

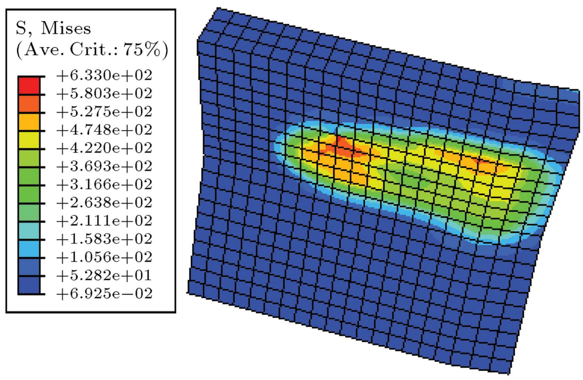

Figure 10. Contour plot of the Von-Mises stress on the die inner surface.

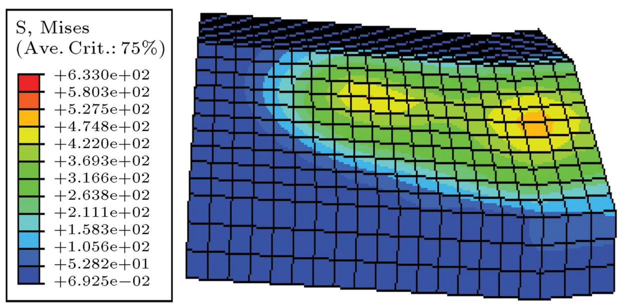

Figure 11. Contour plot of the Von-Mises stress on the die outer surface.

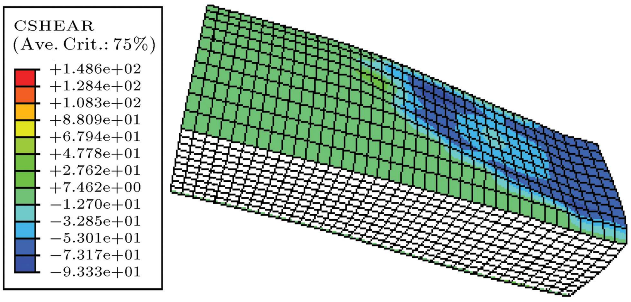

Figure 12. Contour plot of the contact shear stress on the workpiece outer surface.

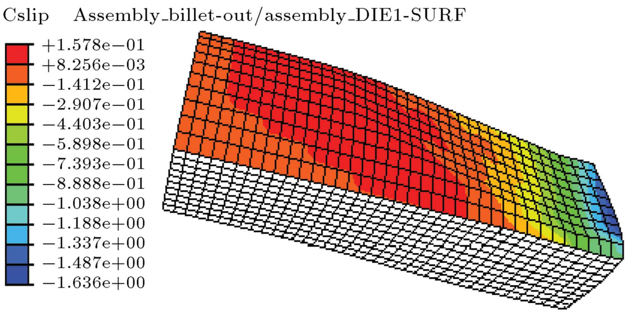

Figure 13. Contour plot of the contact sliding length on the workpiece outer surface.

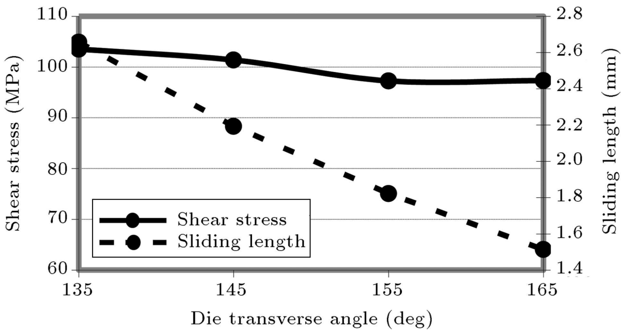

Figure 14. Shear stress and sliding length on the die/workpiece interface.

energy per area, which is the measure of die wear, is maximum there. These regions of die are also where the Von Mises stress is maximum.

4.2. Die transverse angle

Figure 14 shows the sliding length at the die/workpiece interface and the shear stress on this surface for different die transverse angles. Similar to the effects of inlet angle, the increasing of the transverse angle does not affect shear stress significantly, but the sliding length decreases. This is due to the fact that for smaller transverse angles, forging dies better encircle the workpiece and apply more plastic deformation on it. Thus, the flow of the workpiece material on the die surface increases and the sliding length increases, as shown in Figure 14. This matter, as shown in Figure 15, leads to increase of wear at smaller transverse angles.

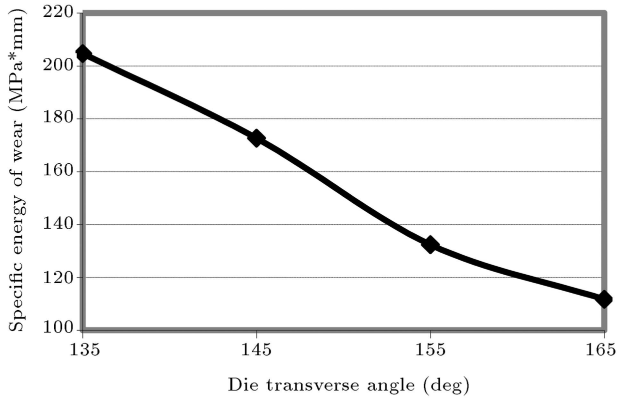

Figure 15. Effect of die transverse angle on the die wear.

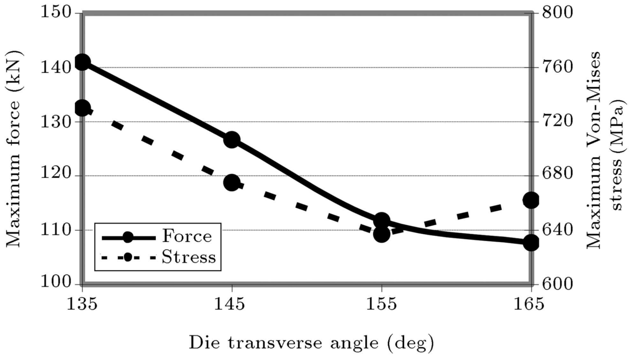

Figure 16. Effect of the die transverse angle on the forging force and stress created in the die.

The increased plastic deformation at smaller angle also raises the forging force, as shown in Figure 16. However, the results show that the smallest value of maximum Von-Mises stress in the die occurs at a transverse angle of 155 degrees. In the radial forging of circular rods, the workpiece contacts each die surface at two points. As the transverse angle increases, these points approach each other on the die surface, such that, at the transverse angle of 180 degrees, there will be just one contacting point. But, the approaching of the contacting points reduces the spread of stress in the die and concentrates it into a smaller region, leading to an increase of stress in that region. Therefore, by increasing the die transverse angle, the applied force and concentration of stress on the die decrease. It seems that the presence of this dual effect causes the smallest maximum Von-Mises stress of the die at the transverse angle of 155 degrees.

4.3. Die land length

Figure 17 shows the shear stress and sliding length on the die/workpiece interface for different die land lengths. At increased land lengths, the frictional shear stress remains almost constant, but the contacting surface between the die and the workpiece is enlarged, leading to an increased sliding length and, thus, wear volume, as shown in Figure 18.

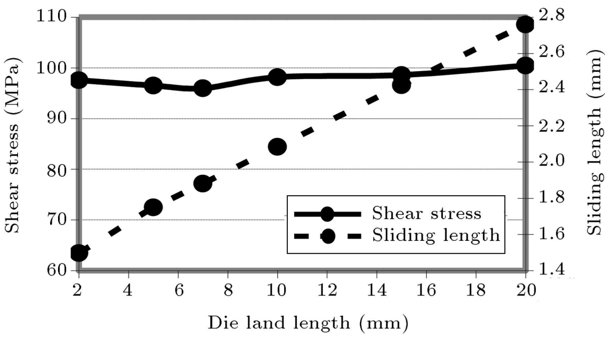

Figure 17. Shear stress and sliding length on the die/workpiece interface.

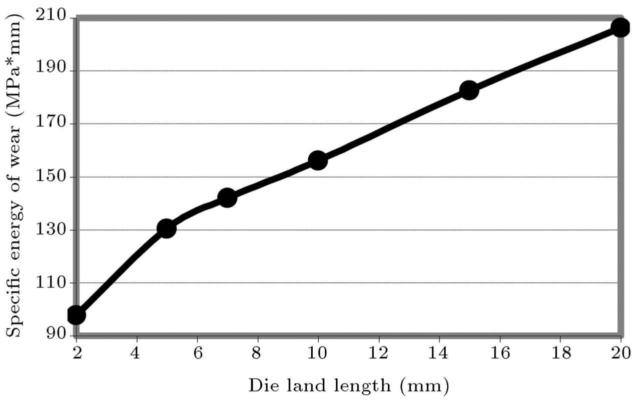

Figure 18. Effect of die land length on the die wear.

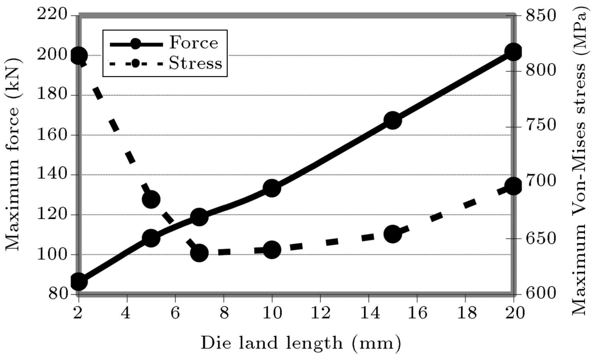

Figure 19. Effect of the die transverse angle on the force and stress created in the die.

Figure 19 shows the force and maximum Von-Mises stress created in the die for different die land lengths. As the land length increases, a bigger portion of workpiece is deformed at every stroke and the forging force increases. This rise in the forging force leads to the increase of stress at larger land lengths. According to Figure 19, this is the case except for very small amounts of land length. It is likely that an excessive decrease of land length leads to a mechanical weakening of the die land and the rising of Von-Mises stress in this region. The land length that seems the best for optimal die life in the studied process is around 7 mm.

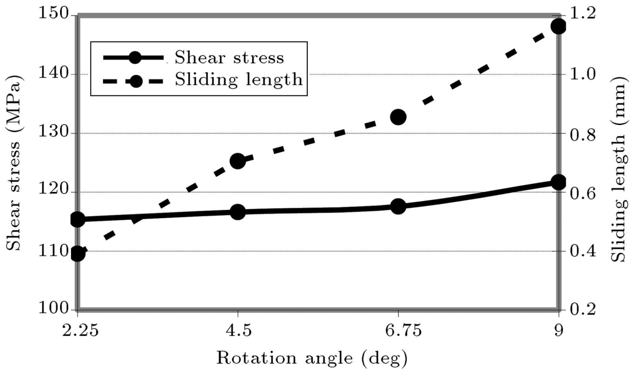

Figure 20. Shear stress and sliding length on the die/workpiece interface.

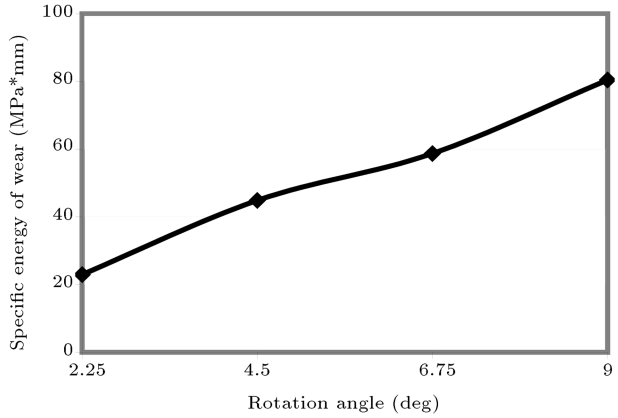

Figure 21. Effect of the workpiece rotational feed rate on the die wear.

4.4. Workpiece rotational feed rate

Besides axial feed, the workpiece is also rotationally fed between strokes. Figure 20 presents the effect of the workpiece rotational feed per stroke on the interfacial shear stress and sliding length. It can be seen that the frictional shear stress at the die/workpiece interface is nearly constant for different values of the workpiece rotational feed, but the sliding length increases. In each die blow, points of the workpiece that are in contact with the die are radially forced towards the workpiece center, while points of the workpiece that lie between the two neighboring dies move further from the center. When the workpiece is rotationally fed between the strokes, these latter points come into contact with the die. At an increase in rotational feed, larger parts of the escaping materials of the last blow are contacted and forced to deform in the current blow. This increases plastic deformation and the workpiece material flow on the die surface in each blow. So, the interfacial sliding length increases, which leads to a rise in die wear volume, as shown in Figure 21.

The increased amount of plastic deformation in each blow also increases the forging force and the maximum Von-Mises stress is created in the die, according to Figure 22. So, similar to axial feed rate, smaller

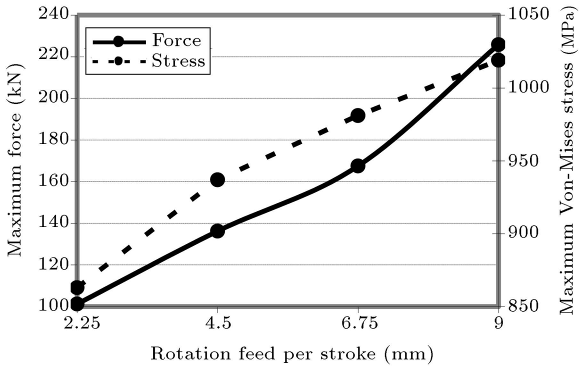

Figure 22. Effect of the workpiece rotational feed rate on the force and stress in the die.

rotational feed results in larger tool life, but reduced production rate.

5. Conclusion

In this study, a nonlinear three dimensional Finite Element Method (FEM) was used for the modeling of a cold radial forging process. The objective was to investigate the effect of die geometry and process parameters on the die life. To this end, wear volume and mechanical fatigue were investigated. Among the parameters considered, the increase of die inlet angle improves die life, while an increase in rotational feed rate has detrimental effects on die life. Furthermore, parameters, such as the die transverse angle and the die land length, have optimum values that represent the largest service life of the die.

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Biographies

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