

## The Relationship between Constant Friction Factor and Coefficient of Friction in Metal Forming Using Finite Element Analysis

SH. Molaei, M. Shahbaz, R. Ebrahimi\*

Department of Materials Science and Engineering, School of Engineering, Shiraz University, Shiraz, Iran

**Abstract:** Frictional shear stress is usually determined by utilizing the coefficient of friction or the constant friction factor models. The present study deals with finite element analysis of double cup extrusion process to determine the relationship between constant friction factor ( $m$ ) and coefficient of friction ( $\mu$ ), since the metal flow in this process is very sensitive to frictional conditions. Therefore, the Finite Element-Code Deform 2D is used which is capable of utilizing both  $\mu$  and  $m$ . According to this analysis, a new equation between constant friction factor ( $m$ ) and coefficient of friction ( $\mu$ ) is suggested. Moreover, in order to evaluate the suggested equation and to compare it with the previous equations, finite element analysis of barrel-compression test is carried out. Finite element results indicate that the new equation can accurately predict the relation between  $m$  and its equivalent  $\mu$  value. The importance of converting these factors to each other is specially highlighted to introduce the frictional conditions in some professional and commercial finite element software.

**Keywords:** Metal forming, Friction coefficient, Constant friction factor, Finite element analysis

### 1. Introduction

Friction is one of the most important factors in metal forming processes, which has an effect on material flow behavior. Mechanical properties of product, die life, internal structure, deforming force and energy requirements are dominated by flow pattern. Beside the detrimental effects of friction such as defect creation through deformation inhomogeneity, wearing off die, etc., friction can also be used beneficially for manipulating the material flow to achieve the desired product with a minimum effort in metal forming processes such as rolling, conform-extrusion and extrusion-forging processes. Therefore, for satisfying the requirements of die design and achieving the sound components, estimation of the frictional condition and its magnitude is an important concern in all metal working processes.

The constant friction model ( $\tau = mk$ ) [1, 2] and coefficient of friction ( $\tau = \mu p$ ) [1, 3] are the important friction models in metal forming analysis, specially in Finite Element Analysis (FEA), where  $p$ ,  $k$ ,  $\mu$  and  $m$  are the normal pressure, shear yield stress, coefficient of friction and the constant friction factor, respectively. In an attempt to obtain quantitative data on friction in metal forming processing, the number of studies has already been made based on these models, using actual metal forming operations or simulative laboratory tests [4]. Double Cup Extrusion (DCE) process [5], upset forging process [6-8] and ring test [9] are mostly used for this purpose.

DCE process is a combination of forward and backward extrusion in which the upper punch moves downwards, while the lower punch and the container are stationary. Thus, frictional condition is different at upper and lower portions. This makes a difference between the height of extruded upper and lower cups in a manner that the ratio between these two heights is controlled by the frictional condition [10, 11]. Figure 1 shows the axisymmetric schematic of DCE test in both initial stage and punch progress during deformation.

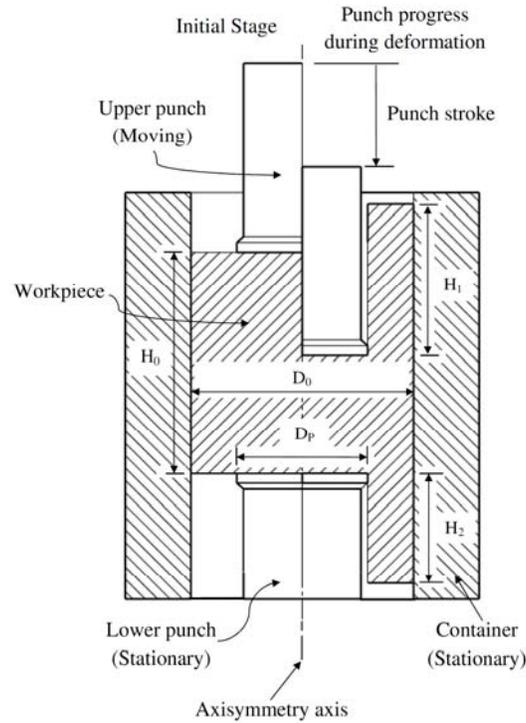


Fig. 1. Axisymmetric schematic of DCE test in both initial stage and during deformation.

Ebrahimi and Najafizadeh developed a new method named Barrel Compression (BC) test to determine the constant friction factor, which involves only the physical measurement of the billet shape changes [12]. In other words, in BC Test there is no need for mechanical properties of the material and the forming loads, whereas the measurement of these parameters presents a major difficulty due to the cumbersome nature of the experiments, especially those at high temperatures and high strain rates. In this test, the effect of frictional condition is determined through measuring the degree of barreling, as [12]:

$$b = 4 \frac{\Delta R}{R} \frac{H}{\Delta H} \quad (1)$$

where

$$R = R_0 \sqrt{\frac{H_0}{H}}$$

$$\Delta R = R_M - R_T$$

and

$$\Delta H = H_0 - H$$

where  $b$ ,  $H$ ,  $H_0$ ,  $R_0$ ,  $R_M$  and  $R_T$  are barreling parameter, height of cylinder after deformation, initial height of cylinder, initial radius of cylinder, cylinder maximum radius after deformation and cylinder top radius after deformation, respectively (Fig. 2). In this test, the barreling parameter increases by severity of frictional condition [13].

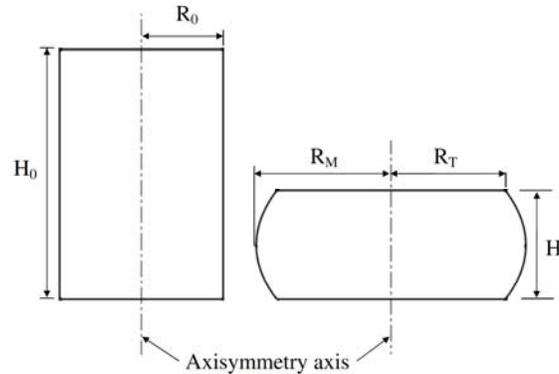


Fig. 2. 2D representation of BC test.

In addition to practical techniques, several numbers of analytical methods such as slab method, slip-line method, upper bound technique, etc., are improved for quantitative analysis of frictional condition. However, the finite element method has been regarded as the most powerful method of analysis in comparison with the above mentioned methods [14]. Development of plastic FEA assists in calculating the local stress, strain, temperature distribution and other practical parameters in metal forming processes and accuracy of the FEA depends on the input data such as material properties and tool-workpiece interface conditions. For this purpose, some professional FE-Codes such as Abaqus, Ansys, Deform, etc., were improved which operate in constant friction factor and/or coefficient of friction. On the other hand, depending on the laboratory equipment or accessories, the measurement of the friction may be based on the constant friction factor, whereas in analysis or commercial FE-Codes, it may be necessary to express the friction through the coefficient of friction. Consequently, it is important to establish a reasonable relationship between these two parameters.

A theoretical relationship between friction factor,  $m$ , and coefficient of friction,  $\mu$ , was driven using slip line method, as [15]:

$$\mu = \frac{m}{\sqrt{27(1-m^2)}} \quad (2)$$

By its nature,  $0 \leq m \leq 1$ , where  $m = 0$  describes one extreme of frictionless condition and  $m = 1$  represents the opposite extreme named sticking friction. Similarly, based on the ring test, an approximate empirical relationship between these two parameters has been suggested as [16]:

$$\mu = \frac{m}{2\sqrt{3}} \quad (3)$$

Equation (2) indicates that  $\mu = 0$  at  $m = 0$  and  $\mu$  leads to infinite at  $m = 1$ , whereas Eq. (3) cannot predict the latter. However, Eq. (3) has the advantages of simplicity in practical range values of friction used in metal forming processes.

In this study, a modified equation is presented in order to relate the constant friction factor and coefficient of friction using FEA of DCE process. For further evaluation of the suggested equation, FEA of BC test was carried out as well.

## 2. Finite element analysis (FEA)

The finite element code Deform2D version 9.0. [17] was used to analyze the DCE process and BC test. The punch and container were assumed rigid due to negligible elastic deformation whereas the billet

material (commercial pure aluminium Al-1050) was considered plastic with the stress-strain relation of  $\bar{\sigma} = 106\bar{\varepsilon}^{0.347}$  MPa, which was determined by compression test at room temperature [18]. Due to axial symmetry in the geometries of BC and DCE, axisymmetric condition was applied in finite element modeling. The workpiece in all simulations was modeled with 3000 tetrahedral elements. Automatic remeshing was used to take into account large strains. Direct iteration method solver was also implemented. The parameters used in FEA of DCE process are listed in Table 1.

Table 1. The parameters used in FEA of DCE process

Diameter of billet, $D_0$ (mm)	28
Height of billet, $H_0$ (mm)	28
Diameter of punch, $D_p$ (mm)	14
Punch velocity, $V_p$ (mm/s)	10

### 3. Simulation results and discussion

Previous investigations on DCE process have shown that the ratio between the height of extruded upper cup and the height of extruded lower cup ( $H_1/H_2$ ) is very sensitive to the reduction ratio,  $r = D_p^2/D_0^2$ , in the range of 0.25 to 0.50 [19]. In  $r = 0.25$ , friction operates at both punch-workpiece and container-workpiece interfaces in the forward extrusion, while in the backward extrusion, friction operates only at the punch-workpiece interface, since there is no relative velocity between container and billet. Hence, the ratio of the cup heights ( $H_1/H_2$ ) increases and the sensitivity to friction enhances [10]. Therefore, in this study the punch diameter was selected based on the  $r$  value of 0.25.

For  $r=0.25$ , the ratio of  $H_1/H_2$  and punch stroke trajectory for the various amounts of constant friction factor in the range of  $0.08 \leq m \leq 1$  were studied using point tracking in FE-Code Deform-2D (Fig. 3). As shown in Fig. 3, there is a similar trend for all selected  $m$  values, so that the ratio of  $H_1/H_2$  after the same punch stroke reaches constant value. A similar trend was found in a study by Buschhausen et al. [20]. The same procedure was also perceived for the various amount of coefficient of friction varying in the range of 0.1-0.577, for  $r = 0.25$  (Fig. 4). Thus, based on the obtained results (Figs. 3 and 4) the punch stroke of 11 mm was selected for all the ongoing analysis.

Using the data in Figs. 3 and 4, with the constant punch stroke of 11mm, the effect of various  $m$ - and  $\mu$ -values on the ratio of  $H_1/H_2$  was investigated (Fig. 5). As seen in Fig. 5, by increasing the severity of frictional condition, the ratio of  $H_1/H_2$  also increases. A similar trend is reported by other researchers as well [20, 21].

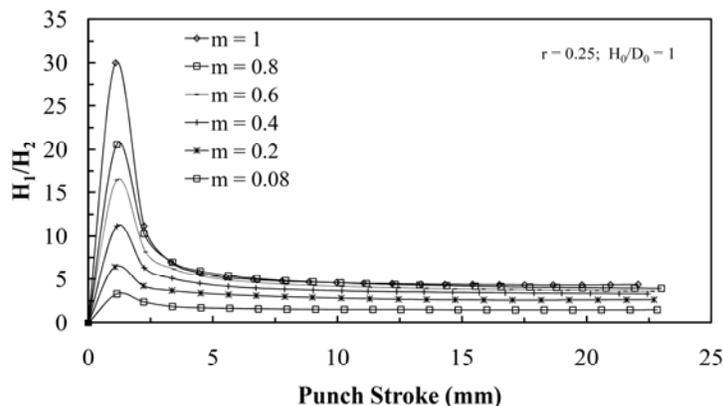


Fig. 3. Variations of  $H_1/H_2$  vs. punch stroke for various values of  $m$ .

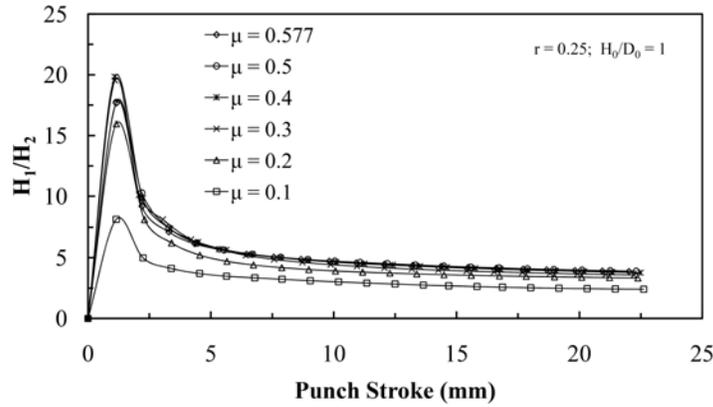


Fig. 4. Variations of  $H_1/H_2$  vs. punch stroke for various values of  $\mu$ .

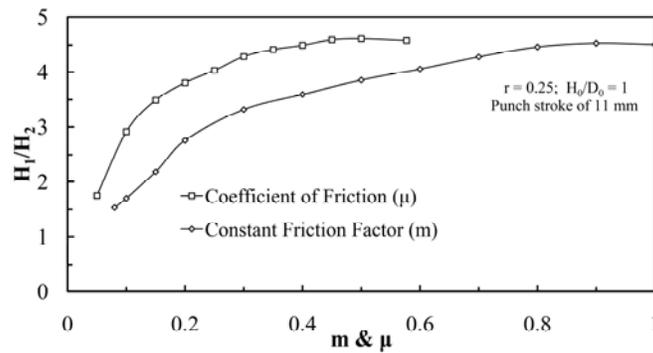


Fig. 5. Effect of  $m$  and  $\mu$  on  $H_1/H_2$  ratio.

Data for  $\mu$  and  $m$  in the same ratio of cup heights based on the depicted results in Fig. 5 were plotted in Fig. 6. Based on the features mentioned in Eq. (2), a similar form was used as the suggested equation for the data in Fig. 6. The numerical constants of this equation were obtained using regression method, as:

$$\mu = \frac{m^{0.9}}{2.72(1-m)^{0.11}} \tag{4}$$

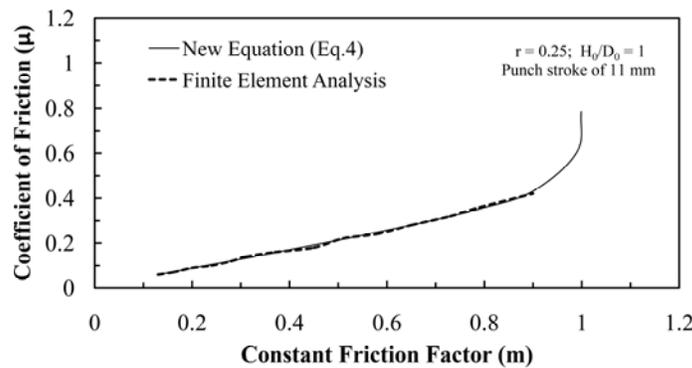


Fig. 6. Diagram of constant friction factor ( $m$ )-values vs. equivalent coefficient of friction ( $\mu$ )-values from Eq. (4), at the same cup heights ratio.

As shown in Fig. 6, the suggested equation matches significantly with FEA data. Moreover, it satisfies the two extremes like Eq. (2). The Eqs. (2), (3) and (4) are shown in Fig. 7 to make the comparison.

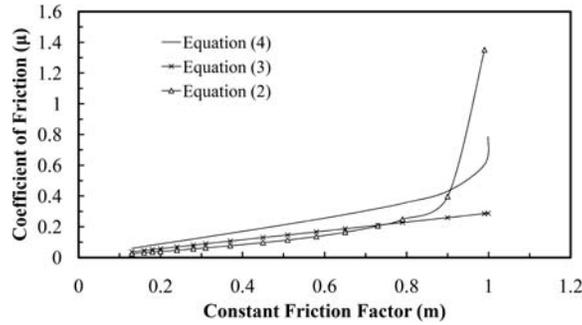


Fig. 7. Comparing the Eqs. (2), (3) and (4).

The axisymmetric simulation of DCE process in punch stroke of 11 mm is exhibited in Fig. 8. To compare the Eqs. 2 and 4 to each other the normal pressure variation between two points on die surface (P1 and P2) were studied by utilizing state variable option in FE-Code DEFORM-2D. Figure 9 displays the pressure distribution between two points of p1 and p2 by considering frictional condition of  $m=0.2$  and  $\mu$  equivalents from Eqs. 2 and 4. According to Fig. 9, the normal pressure obtained for  $m = 0.2$  and  $\mu = 0.09$ , which was calculated from Eq. (4) was more accordant than  $\mu = 0.04$ , which was obtained from Eq. (2). Therefore, this agreement confirms the accuracy of FEA data in developing new equation.

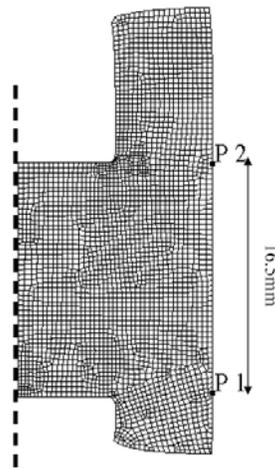


Fig. 8. Axisymmetric FEA simulation of double cup extrusion process for  $r = 0.25$ ,  $m = 0.2$  and punch stroke of 11mm.

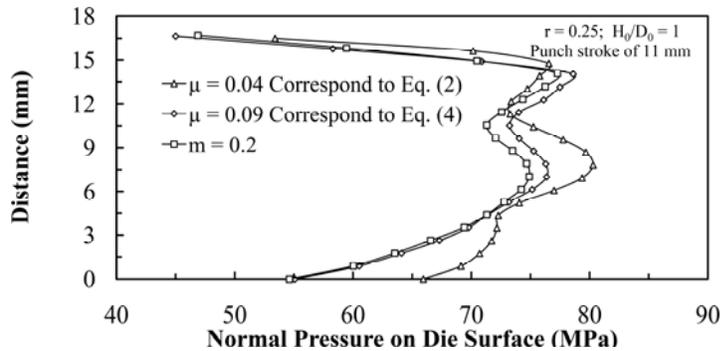


Fig. 9. Variation of normal pressure on die surface between two points p<sub>1</sub> and p<sub>2</sub>.

For more evaluation of the new equation and comparison with Eq. (2), the FEA of BC test for  $m$ -values of 0.1, 0.2 and equivalent  $\mu$ -values obtained from Eqs. (2) and (4) were carried out. Figure 10

shows the axisymmetric schematic of BC test, which was used for FEA. Using geometrical dimensions ( $H$ ,  $H_0$ ,  $R_0$ ,  $R_M$  and  $R_T$ ) during deformation in finite element analysis, barreling parameter is calculated from Eq. (1) for each instance. The results for barreling parameter versus punch stroke of these  $m$ - and  $\mu$ -values are shown in Figs. 11 and 12. As shown in these figures, there is good agreement between the degree of barreling for frictional condition caused by  $m$  value and corresponding  $\mu$  value obtained from Eq. (4), rather than Eq. (2). Consequently, it can be considered as additional evidence to confirm the accuracy of Eq. (4).

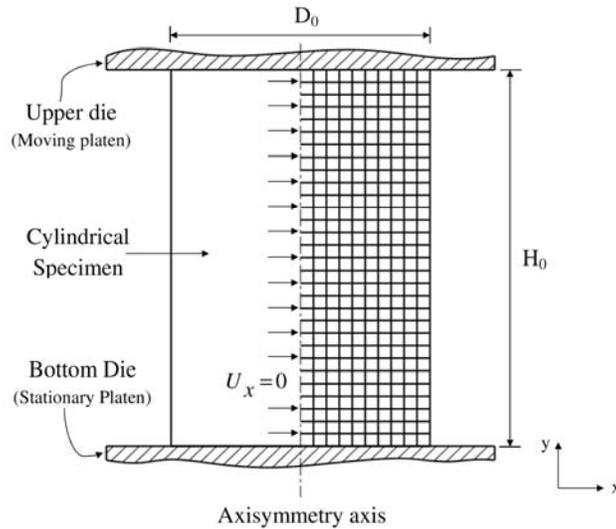


Fig. 10. Axisymmetric schematic of barrel compression test with its boundary condition used in FEA.

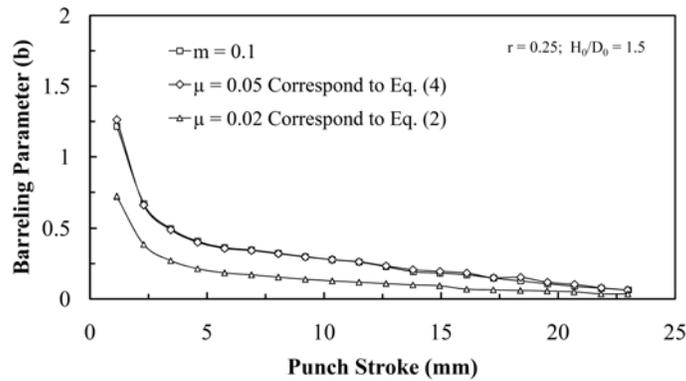


Fig. 11. Variation of barreling parameter vs. punch stroke in BC test.

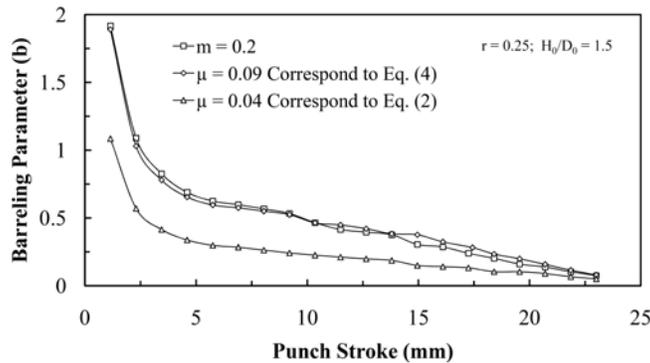


Fig. 12. Variation of barreling parameter vs. punch stroke in BC test.

#### 4. Conclusion

Nowadays finite element analysis with experimental work is used commonly for exact analysis of metal forming processes. Therefore, in this study the FEA of double cup extrusion process was used to obtain the relationship between constant friction factor ( $m$ ) and coefficient of friction ( $\mu$ ). The new equation can be beneficial in some commercial FE Codes, where tool-workpiece interface condition should be defined only by  $\mu$ . In addition, finite element analysis of barrel-compression test was used to confirm the accuracy of the new equation. The results obtained from finite element indicate that the degree of barreling based on  $m$  is exactly correspondent to that of barreling based on the equivalent  $\mu$  value obtained from the new equation (Eq. (4)).

#### 5. References

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