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ORIGINAL ARTICLE

Effect of geometrical and process parameters on coefficient of friction in deep drawing process at the flange and the radius regions

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Abstract In the deep drawing process analyses, generally a single friction coefficient is taken into account for the flange and radius regions of the dies. In fact, friction coefficients between these regions and sheet metal are different from each other. Using of a single friction coefficient for different regions would lead to performing of unreal analyses. In this study, coefficient of friction which is one of the most important parameters affects the deep drawing process for flange and radius regions were determined experimentally. A new friction test apparatus which could determine the friction coefficients for both the flange and the radius regions with only a single experiment was designed and manufactured. Hence, the time and the cost have been reduced. After the tests, it was shown that the friction coefficients are considerably different from each other. By the help of the determined friction coefficients for flange and radius regions contacting to sheet metal, it is concluded that deep drawing analyses can yield more accurate results; thus, time, labor force, and money consumption because of trial-and-error process can be eliminated during die design and process analyses. For this purpose, case studies were experimentally and numerically conducted by using the obtained friction coefficients for flange and radius regions so as to validate the results. Moreover, effect of die radius, surface roughness of the tools, drawing speed, blank holder force, and lubrication type on dynamic coefficient friction between flange and radius regions of the tools and sheet metal were investigated by using ANOVA analysis method. According to the results, lubricant type was found to be an effective parameter for the flange and radius regions. On the other hand, the next effective parameter was surface roughness of the tools and the die radius for radius region, the blank holder force, and drawing speed have small effect for both flange and radius regions. The suitability of separately using of coefficients of friction for the flange and radius regions was verified to obtain closer results to the process.

Highlights 1. The obtained coefficients of friction between the flange and the die radius regions are significantly different from each other.
2. The lubrication condition is the most effective parameter on the coefficient of friction for both the flange and the die radius regions.
3. The mean die surface roughness is the next effective factor on the coefficient of friction for both the flange and the die radius regions.
The separate use of coefficients of friction for the flange and radius regions gave closer results to the process.

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Keywords ANOVA · Coefficient of friction · Deep drawing process · Case study

1 Introduction

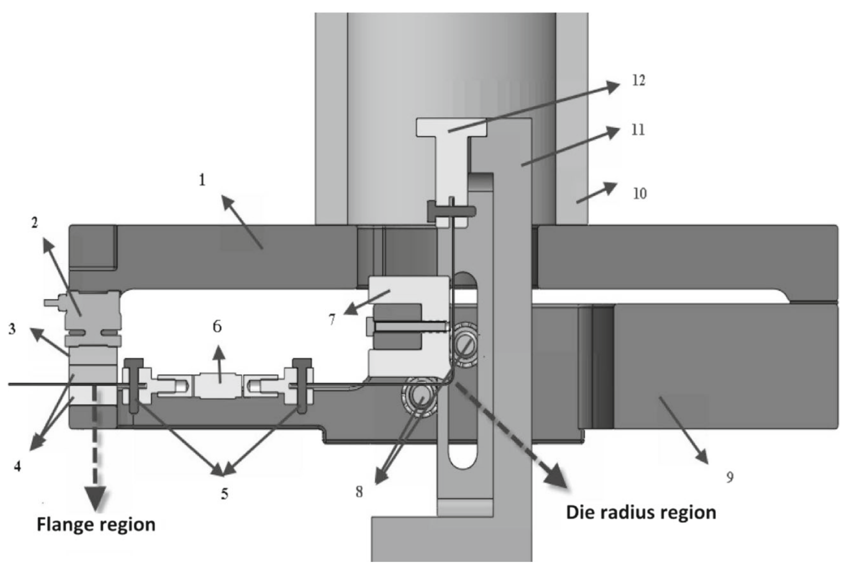
In the past years, design of sheet metal die has taken a long time and die design have been conducted by using trial-and-error method. Sheet metal forming simulation is a powerful technique for predicting the formability of parts and has increasingly become an important tool for the process optimization [1, 2]. These simulations provide a significant reduction in both cost and time compared with the use of die trial-and-error method that is a very time- and cost-consuming. However, it is very important that the material and the process parameters are correctly determined so as to obtain the results close the real results [3]. One of the most important of these parameters is coefficient

Table 1 Comparison of the coefficient of friction test devices

Type of friction device	Advantage	Disadvantage
Strip drawing test	• Use standard tensile machine • Measure only drawing force • The test apparatus is simple	• Determine only coefficient of friction between blank holder and sheet
Radial strip drawing test	• Use standard tensile machine • Measure only drawing force • The test apparatus is simple	• Determine only coefficient of friction between die radius and sheet • Bending before the test • Bending and unbending effects are not included.
Drawbead simulator	• Use standard tensile machine • Modeled the sheet metal flow on the die radius and shoulder	• Determine only coefficient of friction between drawbead • Test apparatus is complex
New friction test apparatus	• Determine simultaneously coefficients of friction between both sheet-blank holder and sheet-die radius with only a single experiment • Reduce the time and the cost. • Obtaining different coefficient of frictions for different regions provide closer to the real results. • The test apparatus is simple	• Use only double action press

of friction which significantly affects the sheet metal forming process [4–7]. Friction forces between the sheet and the tools play an important role due to their effects on the process and the final product [6–10]. The use of inaccurate coefficient of friction can have a significant effect on the FEM simulation [9, 11]. Hence, the coefficient of friction in the process should be determined by experiments representing the real forming process. While material properties used for process parameters are obtained with standard tests, the values in the literature are used for coefficient of friction [12]. It is important that lubrication type, tool material, and workpiece material used in manufacturing processes should be used in friction tests to perform this requirement [6]. Gowtham et al. [13] determined effect of the die radius on deep drawing process keeping the friction, punch

Fig. 1 The designed friction test apparatus



1. Upper body
2. Miniature compression load cell
3. Connection element of load cell
4. Bottom and top flange friction element
5. Connection pins
6. Tension load cell
7. Radius friction element
8. Radius support pins
9. Bottom body
10. Connection element
11. Punch
12. Sheet connection element

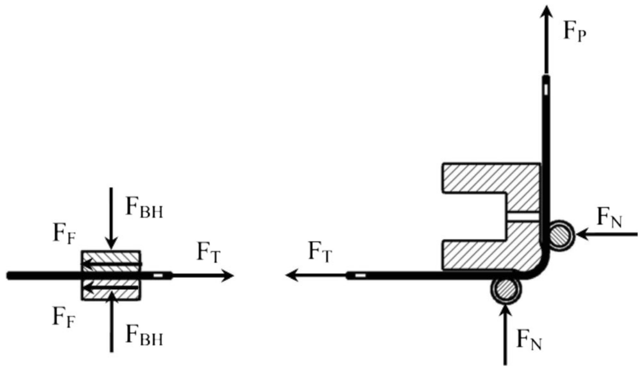


Fig. 2 The measured or calculated forces

radius, and blank thickness as constant. They found that as the die radius is reduced, the amount of force required to draw the material is increased. They observed that a die radius of 7 mm gave an optimum deform levels with minimum damage. Padmanabhan et al. [8] studied the effect of important process parameters namely die radius, blank holder force, and coefficient of friction on the deep drawing characteristics of a stainless steel axisymmetric cup. Klocke et al. [14] has numerically demonstrated that the contact pressure and the slip rate are effective factors on the coefficient of friction under contact conditions typical for sheet metal forming using friction models. Jeon and Barmley [15] described an approach that seeks to describe friction by modeling the geometric surface roughness of the tool to obtain more accurate results for microforming applications. They verified the simulation results with experimental results. Wang et al. [16] investigated the effect of lubrication condition on punch load, surface profile, reduction of thickness, and accuracy of inner diameter using diamond-like carbon film and polyethylene film for microforming process. Dannong et al. [17] studied the influence of lubricants on sheet metal formation under different conditions using a simulating testing machine which uses probes.

The coefficient of friction is often taken the same between the sheet and blank holder and/or the die and between the sheet and the die radius in the drawing processes' finite element (FE) simulations [8]. This is a very poor description of the real behavior. Use of a single friction factor for different regions would lead to performing of unreal analyses [6]. In reality, the coefficient of friction between the sheet and blank holder and between the sheet and the die radius is different.

The determination of the coefficient of friction for different regions separately will provide closer to the real results. So, a significant reduction in respect to cost and time will be obtained in die design and in process analysis, compared with the use of die trial-and-error method that is a very time- and cost-consuming [18].

Various friction test devices such as flat die simulator and radial strip drawing test, strip deep drawing test, and drawbead simulator [5] have been developed in order to determine the coefficient of friction [4, 5, 18]. Wang et al. [19] developed a new test apparatus determining effect of die radii and lubrication condition on coefficient of friction. Fratini et al. [20] designed a new device in order to develop their experiments. They investigated effects of a low pressure and lubricating conditions on sheet metal forming operations for AISI 304. Hao et al. [11] developed a new friction test apparatus which can measure coefficient of friction as a metal strip is pulled over the cylindrical surface of a metal pin. They studied the effects of test variables on the measured coefficient of friction using this apparatus. Strip deep drawing test is actually a combination of the flat die simulator and the radial strip drawing test. These apparatus can determine coefficient of friction for only one region in deep drawing process. A comparative table of the coefficient of friction test devices is given in Table 1. In literature, coefficient of friction is often taken the same between the sheet and the die and the sheet and the blank holder in the drawing processes' FE simulations. Moreover, there are limited studies related to effect of geometrical and process parameters on coefficient of friction.

The conventional and hydromechanical deep drawing processes are widely used in many industries. The use of accurate coefficient of friction has very important effect on the simulation of the processes. The determination of the coefficient of friction for different regions separately contributes to obtain

Table 2 The factors and their levels

Factors	Levels		
	1	2	3
A: die radius (mm)	5	7	10
B: mean die surface roughness (μm)	0.20	0.50	2.30
C: drawing speed (mm/min)	0.5	1.5	4.5
D: blank holder force (daN)	250	500	750
E: lubrication	Dry	Two-layer polyethylene (with 0.04-mm thickness) + Wisura lubrications	Two-layer polyethylene (with 0.04-mm thickness) + paraffin

Table 3 L18 orthogonal array

Test number	A (mm)	B (μm)	C (mm/min)	D (daN)	E
1	5	0.20	0.5	250	Dry
2	5	0.50	1.5	500	Wisura lub. + two-layer poly.
3	5	2.30	4.5	750	Paraffin + two-layer poly.
4	7	0.20	0.5	500	Wisura lub. + two-layer poly.
5	7	0.50	1.5	750	Paraffin + two-layer poly.
6	7	2.30	4.5	250	Dry
7	10	0.20	1.5	250	Paraffin + two-layer poly.
8	10	0.50	4.5	500	Dry
9	10	2.30	0.5	750	Wisura lub. + two-layer poly.
10	5	0.20	4.5	750	Wisura lub. + two-layer poly.
11	5	0.50	0.5	250	Paraffin + two-layer poly.
12	5	2.30	1.5	500	Dry
13	7	0.20	1.5	750	Dry
14	7	0.50	4.5	250	Wisura lub. + two-layer poly.
15	7	2.30	0.5	500	Paraffin + two-layer poly.
16	10	0.20	4.5	500	Paraffin + two-layer poly.
17	10	0.50	0.5	750	Dry
18	10	2.30	1.5	250	Wisura lub. + two-layer poly.

closer to the real results. So, a significant reduction in respect to cost and time will be obtained in die design and in process analysis, compared with using coefficient of friction with trial-and-error method that is a very time- and cost-consuming and so will be contributed to the literature extensively.

In this study, a new friction test apparatus which could specify the coefficients of friction for both the flange and the radius regions with only a single experiment was designed and manufactured. The test apparatus is simple and offers the advantage that strip tensions are measured directly. By means of using this apparatus, difficulties with measuring strain and uncertainties about material deformation descriptions needed to calculate forces from measured strains were eliminated. Case studies were experimentally and numerically conducted by using the obtained coefficients of friction for flange and radius regions so as to validate the results. Moreover, effect of die radius, surface roughness of the tools, drawing speed, blank holder force, and lubrication type on coefficients of friction between flange and radius regions of the tools and sheet metal were investigated by using analysis of variance (ANOVA) analysis method [21].

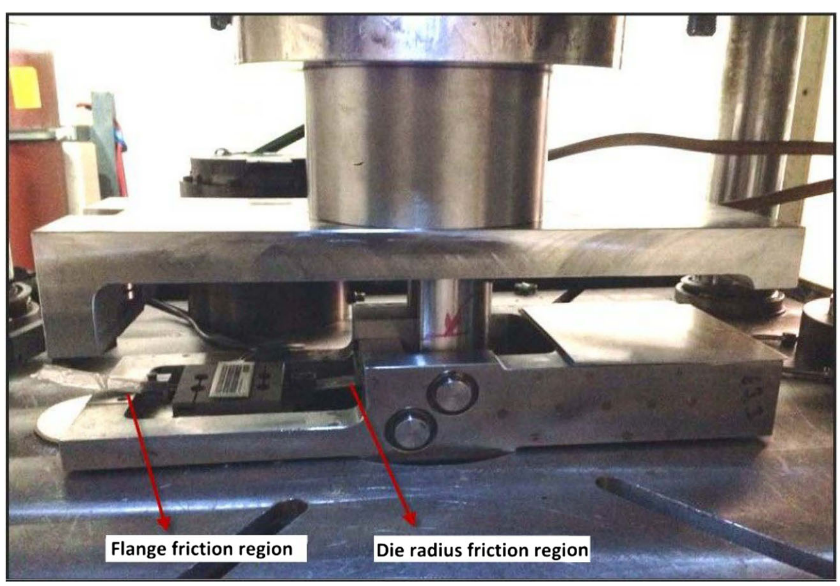


Fig. 3 The friction test apparatus

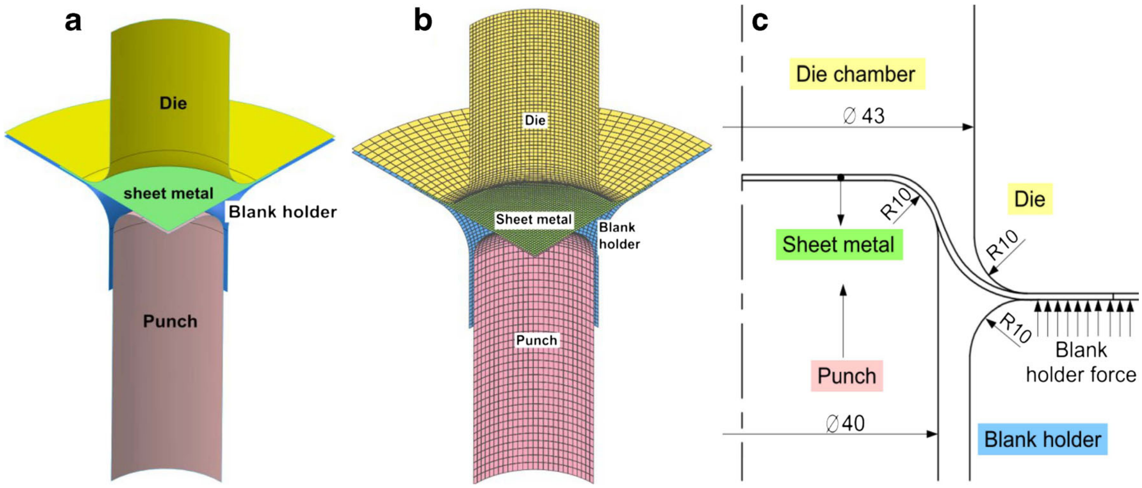


Fig. 4 **a** Surface model, **b** mesh model, and **c** dimensions of the deep drawing process

2 Material and method

2.1 Design of new friction apparatus

In the current study, a new friction test apparatus including the flat die simulator and the radial strip drawing test was designed in a way to assemble to a double action press with hydraulic numeric control (HNC). Since the press moves vertically, the flat die simulator and the radial strip drawing test could not be individually designed. Considering the principles of these apparatus, a new apparatus shown in Fig. 1 was designed and manufactured.

Drawing tests were conducted on the two friction regions called as flange and radius friction regions. Nomenclatures of measured or calculated forces are shown in Fig. 2. In the experiments, the coefficient of friction for the flange region (f_1) was determined by using the tensile force (F_T) measured from the load cell and the blank holder force (F_{BH}) read from the control system of the press. The coefficient of friction for the flange region is

$$f_1 = \frac{F_T}{2F_{BH}} \tag{1}$$

The coefficient of friction for the radius region is calculated using the punch force (F_P) read from the press control system and the tensile force (F_T) in the Euler equation [12, 20].

$$f_2 = \frac{2}{\pi}\ln\frac{F_P}{F_T} \tag{2}$$

The coefficient of friction for the punch sheet could be sensitively determined. However, since the load cell on blank holder of the press has approximately capacity of 700 kN with precision of 10 kN, F_{BH} could not been measured. Hence, the coefficient of friction for the blank holder sheet could not also be sensitively determined. A miniature compression load cell (2) which is not affected from the axial loads was located on the flange region of the apparatus in order to overcome this problem. So, F_{BH} force could be sensitively measured by overcoming this problem and by eliminating friction forces on the columns of the press.

The two strip specimens were connected to a tension load cell (6) so as to be able to measure the F_T force. The bottom of the body (9) is moved toward to the upper body, and thus, the flat strip specimen is pressed between the bottom and top flange friction elements (4). Then, the punch (11) moves upper; the radius strip specimen is drawn upward via sheet connection element (12) connected to the punch (11). While the flat strip specimen scrapes on the friction region between the bottom and top flange friction elements (4), the inclined strip specimen scrapes on the radius friction element (7). In the

Table 4 Coefficients of friction used in the finite element model

Coefficient of friction between	Sheet punch	Sheet-die radius	Sheet-blank holder radius	Sheet-blank holder
Simulation 1	0.43	0.43	0.43	0.25
Simulation 2	0.25	0.25	0.25	0.25
Simulation 3	0.25	0.25	0.25	0.05
Simulation 4	0.43	0.43	0.43	0.05

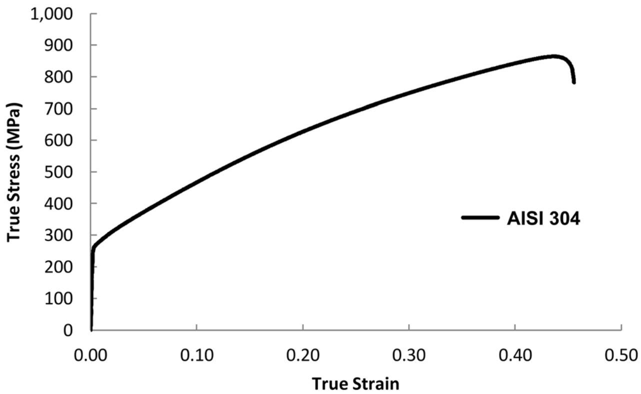


Fig. 5 The true stress-true strain curves used in the model for the AISI 304 material

design, the radius of the radius friction element (7) can be changed from 2 to 37.5 mm. Since the friction tests can be able to match with the real forming process, the friction elements at the flange and the radius regions were manufactured in a way to match material, mechanical properties, and surface roughness of the tools in the deep drawing process and their surfaces were hardened.

The flange (4) and radius friction elements (7) were manufactured from the material of the die being used in the deep drawing process and hardened in order to close the experiments to the real conditions. Support pins (8) were designed and assembled to the two holes on the bottom body so as to balance the forces which force to bend the sheet at the connection point of the radius friction surface of the radius friction element (7). These pins (8) can freely rotate by the help of the journal bearings which mounted the bottom body (9). The strip specimens did not show smearing tendency on the circular friction surfaces of the radius friction element (7) and were formed properly circular geometry due to force effect by means of these pins. Moreover, friction tests can be conducted for various strip thicknesses by using the pin which has the different middle diameter.

2.2 Design of experiment

The design of experiment is a powerful tool for improvement of production processes. It is inevitable that statistical design of experiment methods are used in order to economically determine effective process parameters in short time. Taguchi method is one of the design of experiment methods in which the variability in the product or process minimizes in choosing the optimum levels [22–24].

In this study, effect of die radius, surface roughness of the tools, drawing speed, blank holder force, and lubrication type on dynamic coefficient friction between flange and radius regions of the tools and sheet metal were investigated by using ANOVA analysis method. The matrix experiments were used to determine the effective parameters on the dynamic coefficient of friction. Conducting matrix experiments using special matrices, called orthogonal arrays, allows the influences of several parameters to be specified efficiently and is an important technique in robust design [24]. In this study, three-level L18 orthogonal array was used to inspect the effect of five factors according to Taguchi's design of experiment method (DOE). Each test was repeated three times. Totally, 18 experiments were carried out. When the full factorial experiments were realized, 125 (5^3) experiments must be done. The factors and their levels are given in Table 2.

In total, 18 experiments were carried out according to L18 orthogonal array as given in Table 3. The coefficient of friction value is the only selected performance characteristic. This performance characteristic is higher-the-better type of characteristic. The results were statistically analyzed by the ANOVA method. The significance of the parameters with their contribution ratios to the results and their appropriate levels could be determined by using the ANOVA method. In the ANOVA method, the signal-to-noise (S/N) ratio (objective

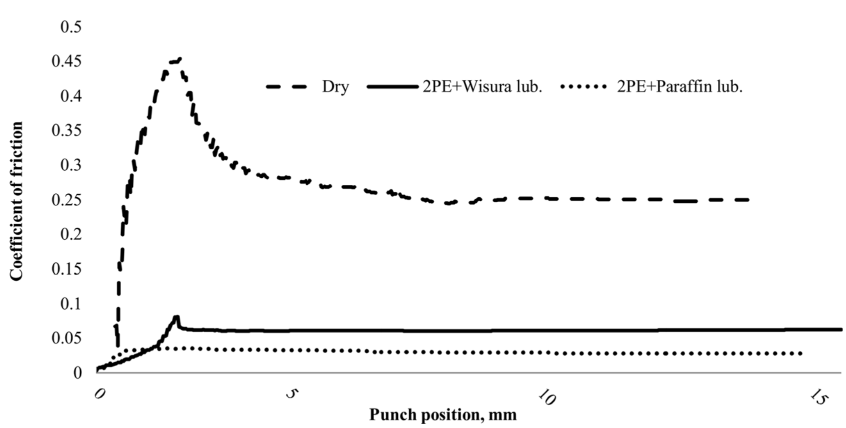


Fig. 6 The coefficient of friction curves between the flange (AISI 4140)—the sheet (AISI 304) for various lubrication conditions **a** with dry, **b** with 2PE + Wisura, and **c** with 2PE + paraffin

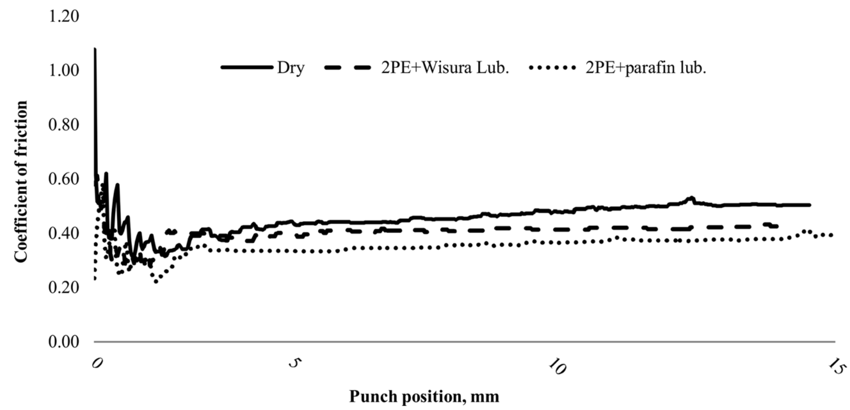


Fig. 7 The coefficient of friction curves between the die radius (AISI 4140)—the sheet (AISI 304) for various lubrication conditions **a** with dry, **b** with 2PE + Wisura, and **c** with 2PE + paraffin

functions) is calculated by using Eq. 3 for every quality characteristics.

$$\eta = -10log\left(\frac{1}{quality\ characteristics}\right)^2 \quad (3)$$

The effect of a parameter level is found with the average of the related results with that parameter's level. For example, the effects of the first level of *A* parameter (m_{A1}) are found by Eq. (4).

$$m_{A1} = \frac{1}{3}(\eta_1 + \eta_2 + \eta_3) \quad (4)$$

The sum of squares of the *A* parameter is found by Eq. (5).

$$= 3\left((m_{A1}-m)^2 + (m_{A2}-m)^2 + (m_{A3}-m)^2\right) \quad (5)$$

where *m* is the overall mean of the η. The sum of squares then divided the degree of freedom of every parameter, and mean squares of the parameters are determined. Degree of freedom is equal to 1 minus the level number. The variation ratio is calculated by dividing the mean square of each parameter by the error mean square. Error mean square is calculated by adding the minimum values of sum of squares up to the number of parameters. The contribution ratio is defined as the ratio

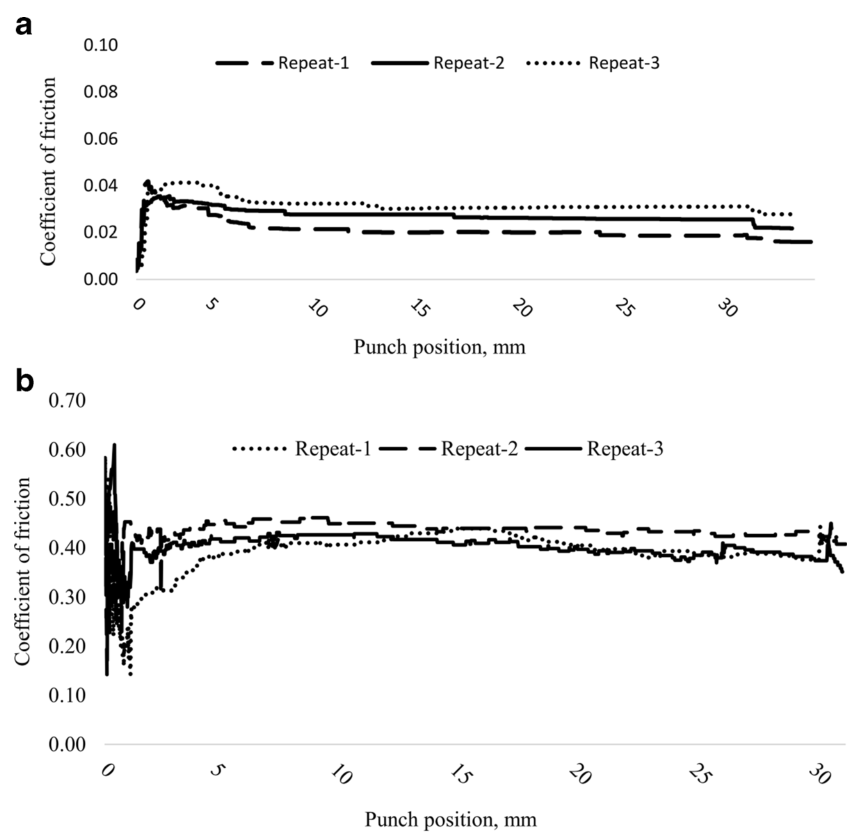


Fig. 8 The repeatability of the coefficient of friction curves between **a** the blank holder—the sheet and **b** the die radius—the sheet for 2PE + Wisura (test 7) lubrication condition

Table 5 Test results and objective functions

Test number	Mean dynamic coefficient of friction between the sheet and the flange	Mean dynamic coefficient of friction between the sheet and die radius	Objective function for flange region	Objective function for die radius region
1	0.25	0.43	12.0412	7.330631
2	0.05	0.42	25.43383	7.535014
3	0.05	0.43	25.43161	7.330631
4	0.06	0.41	25.10446	7.744323
5	0.02	0.40	36.18239	7.9588
6	0.35	0.48	9.118639	6.375175
7	0.03	0.39	29.77673	8.178708
8	0.28	0.44	11.05684	7.130946
9	0.06	0.42	24.76997	7.535014
10	0.03	0.44	30.03719	7.130946
11	0.02	0.46	32.76144	6.744843
12	0.33	0.45	9.629721	6.93575
13	0.27	0.42	11.37272	7.535014
14	0.05	0.46	26.10542	6.744843
15	0.06	0.50	24.66902	6.0206
16	0.02	0.38	33.90256	8.404328
17	0.29	0.50	10.75204	6.0206
18	0.08	0.41	21.9382	7.744323
Overall mean	0.128	0.436	22.227	7.244
Standard deviation	0.12	0.03	8.90	0.66

The coefficients of friction are the mean of three repeats

of each parameter's sum of square to the total sum of square. Finally, the effect of each parameter was found with the contribution ratio which is the ratio of each parameter's sum of square to the total sum of square.

2.3 Friction tests

In this study, AISI 304 stainless steel material was used. The thickness of the specimens is 1 mm. The friction specimens were prepared. The dimensions of the specimens are 15 × 130 and 15 × 200 mm for flange and radius regions, respectively. Before the tests, dirt and oil layers on the surfaces of the specimens and tools were cleaned up with acetone. Then, the surfaces of some specimens were lubricated with paraffin, two pieces of polyethylene having 0.04-mm thickness and Wisura lubrications.

The friction tests were conducted according to the Table 3 using the test apparatus as shown in Fig. 3. After the specimens were placed, a particular force applied on the specimen on the flange region. Then, as the punch progress with

Table 6 ANOVA table for the flange region

Test no.	Factor	Average η by factor level 1	2	3	DOF	Sum of square	Mean square	Variation ratio	Contribution ratio
1	A: die radius (mm)	22.56	22.09	22.03	2	0.49	0.25	0.01	0.11
2	B: mean die surface roughness (μm)	23.71	23.72	19.26	2	39.62	19.81	0.44	9.19
3	C: drawing speed (mm/min)	21.68	22.39	22.61	2	1.40	0.70	0.02	0.33
4	D: blank holder force (daN)	21.96	21.63	21.30	2	3.86	1.93	0.04	0.90
5	E: lubrication	15.17	25.56	30.45	2	385.77	192.89	4.25	89.47
Total					10	431.15	43.12		
Error					5	45.38	9.08		

Table 7 ANOVA table for the die radius region

	Average η by factor level				DOF	Sum of square	Mean square	Variation ratio	Contribution ratio
Test no.	Factor	1	2	3					
1	A: die radius (mm)	7.17	7.06	7.50	2	0.32	0.16	0.07	3.62
2	B: mean die surface roughness (μm)	7.72	7.02	6.99	2	1.02	0.51	0.23	11.70
3	C: drawing speed (mm/min)	6.90	7.65	7.19	2	0.86	0.43	0.19	9.80
4	D: blank holder force (daN)	7.19	7.30	7.25	2	0.02	0.01	0.00	0.21
5	E: lubrication	6.89	8.66	7.44	2	6.52	3.26	1.47	74.67
Total					10	8.73	0.87		
Error					5	2.21	0.44		

constant speed, the specimens are drawn between the tools. Desired forces could be applied by means of HNC on the press. The punch position is limited so as to preserve the system.

2.4 Finite element modeling of the deep drawing process

In this study, case studies were conducted to verify the obtained coefficients of friction. Finite element analyses (FEAs) were conducted to test the obtained coefficients of friction and the use of a single value for various situations. A cup was drawn by using deep drawing process, and punch forces were compared with the FEA results.

LS-Dyna FEA software was used to simulate the deep drawing process. The geometric model comprises of four parts including workpiece (sheet metal blank), die, blank holder, and punch. As seen in Fig. 4a, b, only one quarter of the parts was created in order to reduce the computational time of the finite element analysis as the cylindrical deep drawing process is suitable for axisymmetric analysis. Thus, symmetrical boundary conditions were used for the sheet metal blank.

All the parts in the model were modeled as surface (Fig. 4a), and the meshing process was performed (Fig. 4b). Shell elements were used in the model, and dimensions of the deep drawing process were given in Fig. 4c.

The workpiece (sheet metal blank) was modeled as elastic-plastic, and the other components were modeled as rigid body. The sheet metal blank consists of 3200 shell elements and the whole model of 9219 shell elements in total. Quadrilateral element type and Belytschko-Tsay (default) element formulation with 7 integration point (hourglass card was activated) were used for all the parts for rapid and stable analysis. Since different coefficients of friction were to be used for the blank holder and die and their radius regions, different set_shell lists were created for the aforementioned parts and regions. The coefficients of friction used in the model are given in Table 4.

True stress-true strain curve, which was obtained with the conduction of tensile test, for the AISI 304 material is illustrated in Fig. 5. Other material properties of the AISI 304 sheet metal blank were selected from material catalogues and are $E = 2 \times 10^5$ MPa, $\nu = 0.29$, $\rho = 7.26 \times 10^3$ kg/m^3.

The sheet metal blank that is of 80-mm diameter and of 1-mm thickness was used in the FEA. Total simulation time is 0.45 s, and minimum time step size was calculated as 2.5×10^{-7} by the LS-Dyna FEA software. Also, a constant value of 7.5 kN was used for the blank holder force during the simulation of deep drawing process. The die

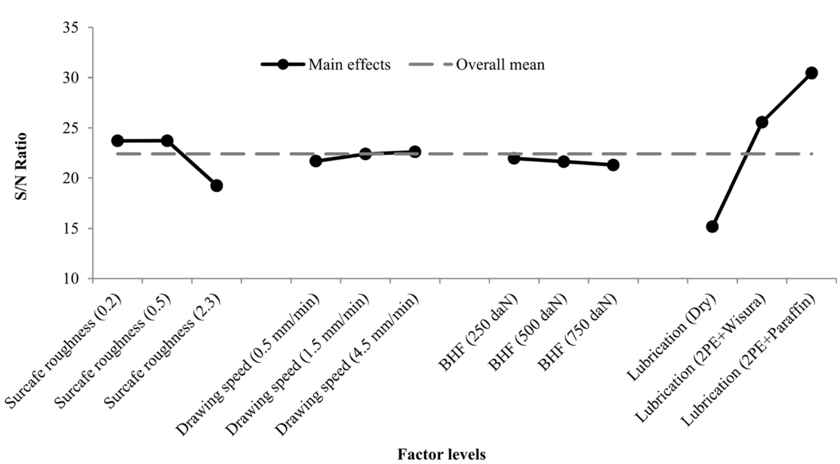


Fig. 9 Plot of factor level for the coefficient of friction between the flange and the sheet

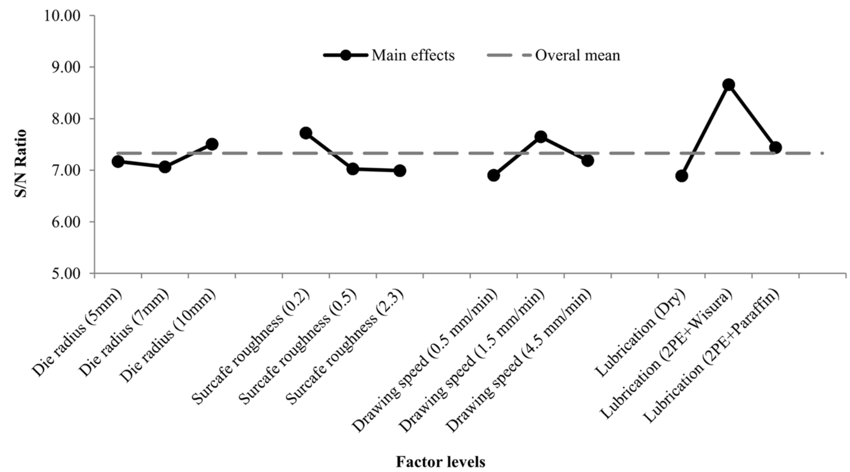


Fig. 10 Plot of factor level for the coefficient of friction between the die radius and the sheet

radius was a constant value of 10 mm for all simulations. The coefficients of friction between the flange and die radius regions are significantly different from each other. So, case studies were conducted to verify the FEA results. Two cups having 40-mm diameter were drawn using the deep drawing process. The first experiment (cup 1) was realized under dry friction condition. The blank holder was only lubricated with the Wisura lubricant for the cup 2. The blank holder force was applied as a constant value of 7.5 kN for all experiments. The sheet metal blank that is of 80-mm diameter and of 1-mm thickness was used in the experiments. The results of the FEA were confirmed by comparing the punch loads of the formed cups by experimentally.

3 Results and discussion

The obtained coefficients of friction curves between the blank holder (AISI 4140)—the sheet (AISI 304)—and the die radius (AISI 4140)—the sheet (AISI 304) were given in Figs. 6 and 7 for dry, 2PE + Wisura and 2PE + paraffin lubrication conditions. These curves are the curves for tests 1, 2 and 7.

The repeatability of the some of the obtained coefficients of friction curves was given in Fig. 8 (for the test 7) for 2PE + paraffin lubrication condition. It is shown that the repeatability of the curves is very good for all conditions. The dynamic coefficients of friction have obtained accuracy of approximately 0.02. Similar results were obtained for the other conditions.

The obtained dynamic coefficient of friction values and their objective functions were given in Table 5 for the performed 18 tests. The ANOVA table was constructed with using the objective functions, and the contribution ratios of each parameter were calculated for the flange and die radius regions as shown in Table 6 and Table 7. As shown in the Table 5, the coefficients of friction between the flange and die radius regions are significantly different from each other. Therefore, the coefficients of friction must be separately used for the flange and radius regions in deep drawing process to obtain close results to the process.

The plots of parameter effects are shown in Figs. 9 and 10 for the coefficient of friction between the flange—the sheet and between the die radius—the sheet, respectively.

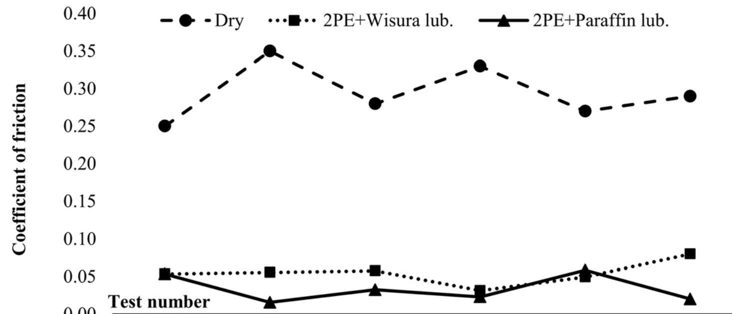
The degrees of influence of the parameters are given Table 8.

The obtained mean dynamic coefficients of friction are given Figs. 11 and 12 for flange and die radii, respectively, for 18 tests in order to compare the effect of lubrication condition. When the Figs. 9, 10, 11, and 12 are analyzed, it is shown that the lubrication condition is the most effective parameter on the coefficient of friction for both the flange and the die radius regions. However, the lubrication condition is a

Table 8 The degree of influence of the parameters

Factor		The degree of influence for the flange region	The degree of influence for the die radius region
1	A: die radius (mm)	–	4
2	B: mean die surface roughness (μm)	2	2
3	C: drawing speed (mm/min)	4	3
4	D: blank holder force (daN)	3	–
5	E: lubrication	1	1

Fig. 11 The mean dynamic coefficients of friction between the flange and the sheet metal for all tests



Test number	1	2	3	4	5	6
Dry	0.25	0.35	0.28	0.33	0.27	0.29
2PE+Wisura lub.	0.05	0.06	0.06	0.03	0.05	0.08
2PE+Paraffin lub.	0.05	0.02	0.03	0.02	0.06	0.02

more effective parameter for the flange region than for the die radius region. This can be explained with the lubricating film thickness that may be not uniform at the radius region even if it can be said that the lubrication condition is not an excessive effective parameter for the die radius region.

The next effective factor on the coefficient of friction is the mean die surface roughness for both the flange and the die radius regions (Figs. 9 and 10, respectively). As the mean die surface roughness increases, the coefficient of friction enhances. In fact, it is expected that the surface roughness is more effective than the others. However, it is required that tests must be conducted for dry condition by holding constant the other factors to determine purely the effect of die surface roughness.

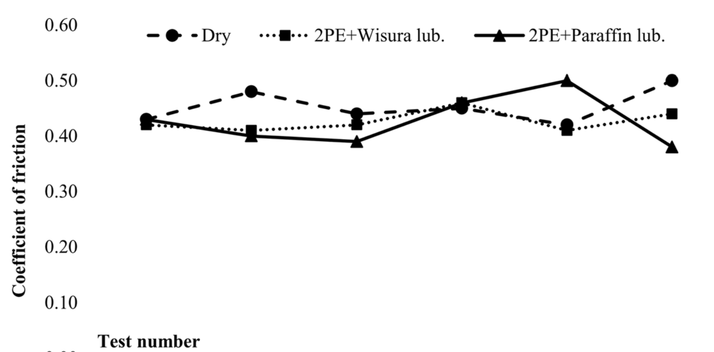
The drawing speed and the blank holder force have small effect on the coefficient of friction for the flange region (Fig. 9). Moreover, the drawing speed and the die radius have also small effect on the coefficient of friction for the flange region (Fig. 10).

Since the coefficients of friction between the flange and die radius regions are significantly different from each other, case studies were conducted to verify the results. The simulation results were compared with the experimental results with regard to the punch forces of the formed cups. The punch forces are taken as the mean of three repeats. The comparison of the use of different coefficient of friction in the simulations and experimental results were given in Fig. 13. As shown in Fig. 13a, the punch force of the cup 1 is in good agreement with the result of the simulation 1. The use of same coefficient of friction values offers improper results. Therefore, it can be said that the separate use of coefficients of friction for the flange and radius regions gives closer results to the process. Figure 13b shows that the use of coefficient of friction value of 0.43 instead of 0.25 is proper for die radius for dry condition as in the real process. In the event of using the value at the flange for the die and die radius, the experimental result is far away from the simulation result.

4 Conclusions

In this research, a new friction test apparatus which could specify the coefficients of friction for both the flange and the radius regions with only a single experiment was designed and manufactured. Effect of die radius, surface roughness of the tools, drawing speed, blank holder force, and lubrication type

Fig. 12 The mean dynamic coefficients of friction between the die radius and the sheet metal for all tests



Test number	1	2	3	4	5	6
Dry	0.43	0.48	0.44	0.45	0.42	0.50
2PE+Wisura lub.	0.42	0.41	0.42	0.46	0.41	0.44
2PE+Paraffin lub.	0.43	0.40	0.39	0.46	0.50	0.38

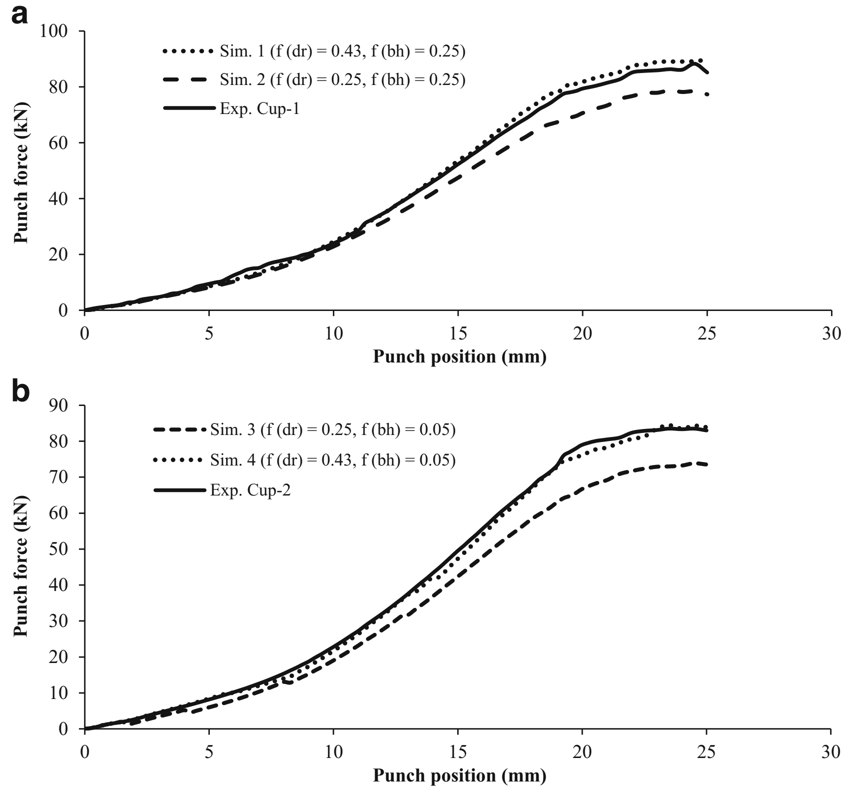


Fig. 13 The comparison of the use of different coefficient of friction in the simulations and experimental results: **a** the cup 1 and **b** the cup 2

on coefficient friction between flange and radius regions of the tools and sheet metal was investigated by using ANOVA analysis method. Case studies were experimentally and numerically conducted by using the obtained coefficients of friction for flange and radius regions so as to validate the results. The following results were drawn:

- In this study, a new friction test apparatus which can determine the friction coefficients for both the flange and the radius regions by a single experiment, different from the other apparatus, was designed and manufactured. The test apparatus is simple. So, it will be able to save time and cost by means of a single experiment. Moreover, obtaining different coefficient of frictions for different regions provides closer to the real results.
- The obtained dynamic coefficients of friction between the flange and die radius regions are significantly different from each other. The dynamic coefficients of friction have obtained accuracy of approximately 0.02. The mean coefficients of friction values under dry condition for the flange and radius regions have been obtained 0.25 and 0.43, respectively. Therefore, the coefficients of friction must be separately used for the flange and radius regions in deep drawing process to obtain close results to the process.
- The lubrication condition is the most effective parameter on the coefficient of friction for both the flange and the die radius regions. However, the lubrication condition is a more effective parameter for the flange region than for the die radius region.
- The mean die surface roughness is the next effective factor on the coefficient of friction for both the flange and the die radius regions, and as the mean die surface roughness increases, the coefficient of friction enhances.
- The drawing speed and the blank holder force have minor effect on the coefficient of friction for the flange region. In addition, the drawing speed and the die radius have also small effect on the coefficient of friction for the flange region.
- The separate use of coefficients of friction for the flange and radius regions gives closer results to the process. So, forming processes can be accurately modeled with using proper coefficients of friction before the manufacturing. Thus, a significant reduction in respect to cost and time will be obtained in die design and in process analysis, compared with the use of die trial-and-error method that is a very time- and cost-consuming. The use of coefficient of friction value of 0.43 instead of 0.25 is proper for die radius for dry condition as in the real process. In the event of using the value at the flange for the die and die radius, the experimental result is far away from the simulation result.
- In future works, the coefficients of friction should be determined for various factors such as strip thickness and temperature.

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