SEMI EMPIRICAL MODELING OF FLOW FORMING PROCESS

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Abstract: Flow forming is plastic deformation process which is widely used to manufacture high precision seamless components for aerospace and defence industries. The other potential applications are pressure gas bottles, thin walled high precision seamless tubes and closed end cylinders for nuclear, chemical, pharmaceutical, food, beverage, cryogenic, printing and filtration industries. There are basically two approaches used during actual production i.e. forward and reverse. In forward approach, the roller feed and deformation directions are same. While, in backward approach, the roller feed and deformation directions are opposite. The online measurement of forces is still difficult in commercial machines. The knowledge of force(s) is quite crutial for tooling (rollers and mandrel) design for different material and geometric environment. Hence, dimensional analysis based semi empirical model has been developed to predict the force(s). This type of practice is used to minimize the number and intricate factors of experiments which influence a given physical occurance, by using compacting method to some extent. Even such method has proven more efficient in other domains like EDM, fluid flow, gas dynamics etc. Therefore, a model is build to predict the force(s) during flow forming process. Three types of variables like operating, tool (roller) geometry and material property parameters have been considered during model development. The results were compared with the simulation model (Bhatt and Raval, 2016) and analytical model (Thomson et al., 1965). The results were found in good conformity with both the models. Thus the estimation of the force(s) via semi empirical model can be effectively used to predict forces for various material and geometric conditions during flow forming process.
Key words: Flow forming, Semi Empirical Model, Dimensional Analysis, Force Prediction

1. INTRODUCTION

Thin walled tubes with high precision are the important components in applications of aerospace and defence industries. Missile casing, rocket motor case, cartridge case etc. are made by flow forming process. Flow forming is a rotary contact deformation process. In this process, a deformable blank is clamped on the rigid mandrel and rollers (rigid) are deforming it in the contact zone. There are basically two approaches used during process i.e. forward and reverse/backward. The deformation of blank/workpiece and roller feed are in the same direction in forward approach (figure 1(a)) whereas the deformation of blank/workpiece and roller feed are opposite in reverse approach (figure 1(b)). During the process, the length of workpiece increases and thickness decreases.

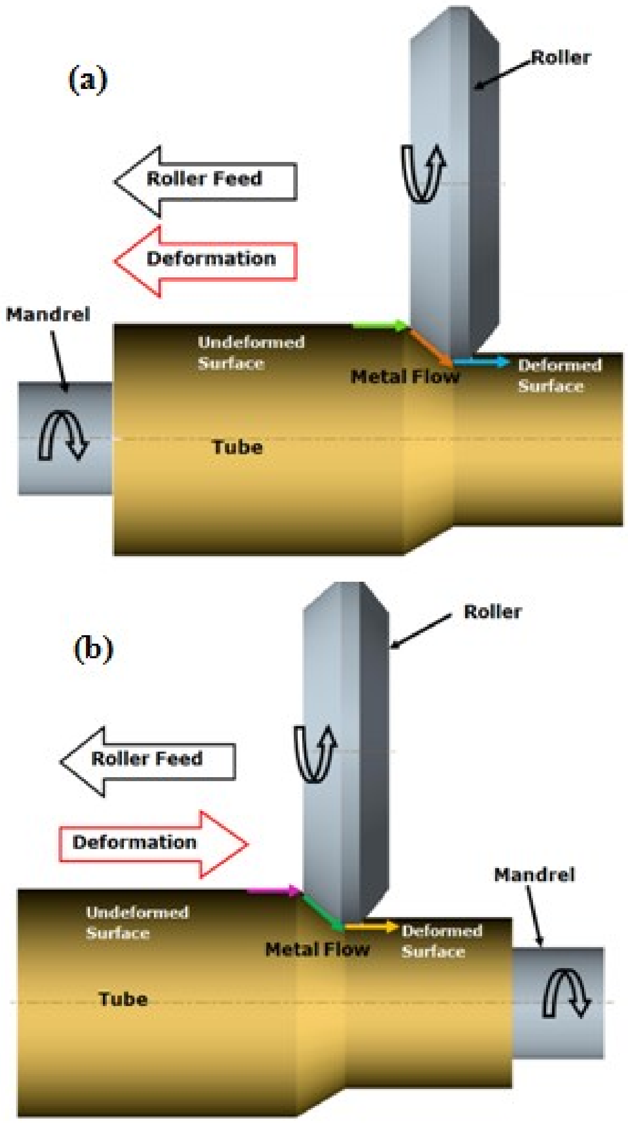

Fig. 1. Flow forming approaches (a) forward (b) reverse/backward

The experimental works were reported to analyze the process during last decade. Cao et al. (2015) had experimentally investigated effect of temperature, feed rate, mandrel speed and percentage reduction on the mechanical properties and microstructure during the hot flow forming process. Srinivasulu et al. (2013) had performed experiments with single roller on CNC flow-forming machine in order to investigate mechanical properties of flow formed tubes. Haghshenas and Klassen (2015) had investigated on mechanical properties of FCC alloys after flow forming process using four different material viz. AA 5052, AA 6061, pure copper, Brass 70/30. Razani et al. (2011) had investigated forward flow forming process using three roller configurations on NC lathe machine using Taguchi method. Later, Razani et al. (2014) had done experimental study on AISI 304 stainless steel using RSM (Box-Behnken design) to analyze the final hardness of workpiece. Nahrekhalaji et al. (2010) had done the experimental study using Taguchi method for different operating conditions such are startin thickness of workpiece, feed rates, solution treatment and aging, mandrel rotational speed, reduction of thickness (%). Molladavoudi et al. (2011) had investigated on surface roughness, hardness and diametral growth for AA7075. Davidson et al. (2008) had carried out experiments to investigate effect of feed rate, depth of cut and rotational speed on mechanical properties using Taguchi technique. Abedini et al. (2014) had investigated on surface roughness using Taguchi L27 design during flow forming process for copper alloy.

The experimental work requires large quantity of tool and workpiece material. Thus, it is uneconmical affair for purely experimental studies. Therefore, numerical based analysis is a good choice to bring down the experiments without much loss of accuracy in the results. That ultimately reduces material and inventory carrying cost. Mohebbi et al. (2010) had numerically investigated the straining pattern during process using ABAQUS. Kim et al. (2013) had analyzed the different roller angles using upper bound method and simulations. Wong et al. (2005) had simulated the flat disc flow forming process for AA6061. Zoghi et al. (2013) had done FE analysis of hot tube necking process for 42CrMo steel. Xia et al. (2006) had done the analysis of flow forming for non axisymmetrical geometry. Shinde et al. (2016) had studied the effect of different parameters during three roller forward flow forming using face-centred central composite design (CCD) for Maraging steel.

Based on literature review and industrial survey, it was observed that the online force measurement and monitoring are quite difficult in commercial machines. Even experimental trials increases indirect cost. The simulations results are also required high end computer hardwares and softwares. Hence, semiempirical model has been developed to predict the force(s). Such method is widely accepted in other areas like fluid flow (Bansal, 2012), gas dynamics, EDM (Wang and Tsai, 2001; Patil and Brahmankar, 2010) etc. The results were compared with the simulation model developed by Bhatt and Raval (2016) and analytical model developed by Thomson et al. (1965).

2. SEMI EMPIRICAL MODEL

2.1 Background

The dimensional analysis is the approach of minimizing the complicated experimental trials. The method can be carried out by two techniques – 1) Rayleigh's method and 2) Buckingham's π theorem. Selection of the method depends on the number of parameters that are involved in the problem. Rayleigh's method is suitable for determining the expression for a variable which depends upon maximum four variables only. When the problem involves higher number of variables, Buckingham's π theorem is more suitable.

Buckingham's π theorem states that "If there are n variables (independent and dependent) in a physical phenomenon and if these variables contain m fundamental dimensions (M, L, T, θ, I), then the variables are arranged into (*n-m*) dimensionless terms. Each term is called π term" (Bansal, 2012)

If X_1 is a dependent parameter and X_2, X_3,...X_n are independent parameters on which X_1 depends, it can be mathematically expressed as under:

$$X_1 = f(X_2, X_3 ... X_n) \qquad (1)$$

It can also be written as:

$$f(X_1, X_2, X_3 ... X_n) \qquad (2)$$

which is a dimensionally analogous equation which contains *n* parameters. If there are *m* elemental dimensions, then the above expression can be written in the form of (*n* – *m*) π terms as under:

$$f(\pi_1, \pi_2, \pi_3 .. \pi_{n-m}) \qquad (3)$$

Each of the π terms is dimensionless and is autonomus of the system. Division or multiplication by a constant does not alter the character of the π term. Each π term contain *m+1* variables, where *m* is the number of basic dimensions and is also called repeating variables.

The selection of repeating variables is governed by the following considerations (Cengel and Cimbala, 2012; Bansal, 2012) (refer table 1):

•Dependent parameters should not be selected as

repeating factor as far as possible.
•Repeating factorss should be selected in such a way that they belong to different categories.
•Repeating factors should not form a dimensionless group.
•Repeating factors jointly must have same number of basic dimensions.
•Two repeating factors should not have same dimensions.

2.2 Model Development

Force (*F*) determination during the flow forming process is very important because tooling design is mainly depending upon forces. Therefore, a model has been developed to predict the forces. There are three force components are acting during flow forming i.e. axial, radial and circumferential. Here, the resultant of these three forces is considered for the model development as shown in figure 2. To develop the model, operating parameters, tool geometry parameters and material property parameters of workpiece has been considered.

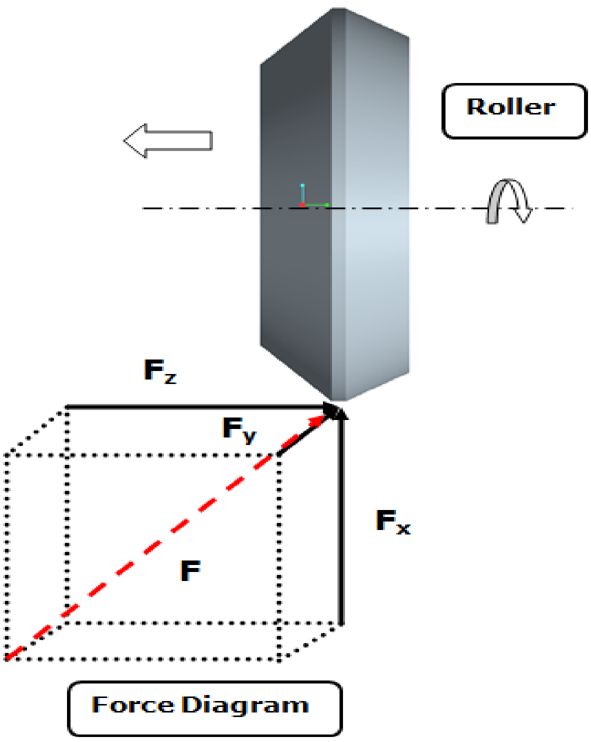

Fig. 2. Force Diagram, [4]

The input parameters are listed below which are used for model development.
1) Operating Variables
Three operating parameters have been selected based on literature survey and preliminary work. The parameters include speed (*S*), feed (*f*) and depth of forming (*FD*). These are the major contributory factors as these can be vary by operator will. Therefore, it is required to consider these three parameters.
2) Tool geometry variables
Normally rigid rollers are used during the process. The configuration of the roller is depending upon the geometry and type of material of workpiece. The parameters include roller diameter (*RD*), roller thickness (*RT*) and roller inclination (*RI*).
3) Material Properties of work material
Flow forming is mainly depending upon the material properties of workpiece material. Because the deformation in any forming process is mainly govern by them. Here, basic material properties like density (*ρ*), yield stress (*YS*) and ultimate tensile strength (*UTS*) are considered for the model development.
The table 1 shows the list of parameters considered for model development along with their symbols and dimensions.

Table 1. Parameters and their dimensions

	Sr. No	Parameters	Unit	Dimension
Repeating	1	Speed (*S*)	RPM	T^{-1}
	2	Depth of Forming (*FD*)	mm	L
	3	Density (*ρ*)	Kg/m^3	ML^{-3}
Non repeating	4	Force (*F*)	N (kg m/s^2)	MLT^{-2}
	5	Feed (*f*)	mm/min	LT^{-1}
	6	Roller diameter (*RD*)	mm	L
	7	Roller thickness (*RT*)	mm	L
	8	Roller inclination (*RI*)	°	Dimensionless
	9	Yield stress (*YS*)	MPa (MN/m^2)	$ML^{-1}T^{-2}$
	10	Ultimate tensile strength (*UTS*)	MPa (MN/m^2)	$ML^{-1}T^{-2}$

In present case, Force (*F*) can be expressed as:

$$Force(F) = f(S, f, FD, RD, RT, RI, \rho, YS, UTS) = 0 \quad (4)$$

$$f(F, S, f, FD, RD, RT, RI, \rho, YS, UTS) = 0 \quad (5)$$

Fundamental dimensions include: M, L, T
Repeating variables: 3
These repeating variables are by using the considerations proposed by Cengel and Cimbala, (2012) and Bansal (2012) as mentioned above.
No. of dimensionless parameters (π- terms) =
Total number of parameters – No. of fundamental dimensions

= 10 – 3 = 7
Non repeating parameters = 7
Now, based on Buckingham's theorem, equation (5) can be written as,

$$f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8) = 0 \quad (6)$$

These π terms can be calculated as follows.

$$\begin{aligned} \pi_1 &= S^a \cdot FD^b \cdot \rho^c \cdot F \\ &= T^{-a} \cdot L^b \cdot \left[ML^{-3}\right]^c \cdot \left[MLT^{-2}\right] \\ \pi_1 &= M^{c+1} \cdot L^{-3c+b+1} \cdot T^{-a-2} \end{aligned} \quad (7)$$

The calculations of power indices are evaluated as:
$\pi_1 = M^{c+1} \cdot L^{-3c+b+1} \cdot T^{-a-2} = M^0 L^0 T^0$
M → c + 1 = 0 then a = -2
L →-3c + b + 1= 0 then b = -4
T → -a - 2 = 0 then c = -1

$$\pi_1 = \frac{F}{S^2 \cdot FD^4 \cdot \rho} \quad (8)$$

Similarly, other π –terms and corresponding power indices can be calculated. After calculating all the π-terms and their power indices the equation (6) can be written as,

$$\pi_1 = A \cdot (\pi_2)^a \cdot (\pi_3)^b \cdot (\pi_4)^c \cdot (\pi_5)^d \cdot (\pi_6)^e \cdot (\pi_7)^f \quad (9)$$

where, *A, a, b, c, d, e, f, g* are constants which can be find out using curve fitting.
On substitution of the expressions for π terms, we get,

$$\frac{F}{S^2 \cdot FD^4 \cdot \rho} = A \cdot \left(\frac{f}{S \cdot FD}\right)^a \cdot \left(\frac{RD}{FD}\right)^b \cdot \left(\frac{RT}{FD}\right)^c \cdot (RI)^d \cdot \left(\frac{YS}{S^2 \cdot FD^2 \cdot \rho}\right)^e \cdot \left(\frac{UTS}{S^2 \cdot FD^2 \cdot \rho}\right)^f \quad (10)$$

Which, can be written as,

$$F = A \cdot S^2 \cdot FD^4 \cdot \rho \cdot \left(\frac{f}{S \cdot FD}\right)^a \cdot \left(\frac{RD}{FD}\right)^b \cdot \left(\frac{RT}{FD}\right)^c \cdot (RI)^d \cdot \left(\frac{YS}{S^2 \cdot FD^2 \cdot \rho}\right)^e \cdot \left(\frac{UTS}{S^2 \cdot FD^2 \cdot \rho}\right)^f \quad (11)$$

The constants in the equation of the resultant force can be found using non-linear estimation. The common agenda of the non linear estimation is to establish relationship between indipendant variables with dependant variables. In present case, gauss-newton method has been used for non linear estimation. The main feature of this model is the incorporation of operating, tooling and material properties. These are considered as to best fit with the simulation and analytical models. The adequacy of the model is checked by the error percentage beween proposed model with simulation and analytical model.

3. RESULTS AND DISCUSSION

The verification of the model has been carried out with two results i.e. 1) simulation model of Bhatt and Raval (2016) and 2) analytical model of Thomson et al. (1965).

3.1 Comparison with simulation model

Bhatt and Raval (2016) had done simulation analaysis considering various parameters (operating and roller geometrical) on forces. In order to verify the proposed model all the material, geometry and operating parameters were kept same with respect to Bhatt and Raval (2016) in which Taguchi L27 array was used for analysis. Table 2 shows the percentage error for the resultant force between semi empirical model and simulation results of Bhatt and Raval (2016). It was observed that maximum absolute percentage error was 8.9291 for run no 19.

Table 2. Comparison of resultant force with error

Run No.	Simulation	Semi empirical Model	Error (%)
1	1330.3958	1389.3746	4.2449
2	1371.6273	1414.3746	3.0223
3	1418.6245	1357.3746	-4.5124
4	3091.6105	3242.645	4.6577
5	2964.6066	2810.5467	-5.4815
6	2857.3558	2999.0125	4.7234
7	4538.3925	4764.7163	4.75
8	4389.9904	4599.0361	4.5454
9	4345.4743	4598.9173	5.5109
10	2509.8975	2729.9740	8.0614
11	2533.5235	2746.3284	7.7487
12	2453.8001	2673.5478	8.2193
13	2180.649	2383.7153	8.5189
14	2127.8044	2301.5412	7.5487
15	2141.5494	2347.8163	8.7854

16	3692.3631	3908.8163	5.5375
17	3617.6297	3399.6293	-6.4125
18	3626.4086	3847.9784	5.7580
19	2101.2176	2307.2343	8.9291
20	2131.156	2298.542	7.2823
21	2048.4346	2229.7264	8.1306
22	3565.1093	3789.8937	5.9311
23	3604.5348	3819.7856	5.6351
24	3630.2777	3799.8263	4.4620
25	2590.2296	2699.4372	4.0455
26	2668.7244	2886.7453	7.5524
27	2572.4969	2704.4247	4.8782
Mean	2818.6623	2964.8504	4.9307
Standard Deviation	889.8626	941.1265	-

Figure 3 shows the variation of resultant force between simulation and semi empirical model. It shows the comparison for 27 simulations of Bhatt and Raval (2016).

It can be said that the semi empirical model has the good conformity with the simulation results with certain variation. It is because; the simulation model is also an approximate method to predict the results which governs by some algorithms like newton raphson, quasi-newton, simplex etc. for convergence phenomenan. Thus, it could be the probable reason for the variation between both the models.

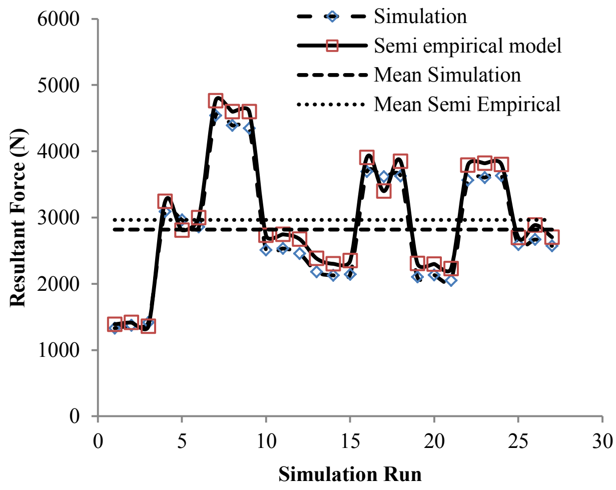

Fig. 3. Comparison of resultant force for all simulation runs

3.2 Comparison with analytical model

Thomson et al. (1965) proposed an analytical model to estimate the forces. The verification of the semi-empirical model has been carried with same model. Equation (12) shows the relationship of the forces.

$$\frac{F_x}{\overline{\sigma'_m} t_i f} = \frac{-F_y}{\overline{\sigma'_m} t_i \sqrt{2Rf/\tan\alpha}} = \frac{F_z}{\overline{\sigma'_m} t_i \sqrt{2Rf\tan\alpha}} \quad (12)$$

where, F_x = radial force, F_y = circumferential force, F_z = axial force, f = feed, R = roller radius, t_i = initial thickness of workpiece, α = leading angle of roller

Here, $\overline{\sigma'_m}$ can be found as,

$$\overline{\sigma'_m} = \frac{2}{\sqrt{3}} \overline{\sigma_m} \quad (13)$$

where, $\overline{\sigma_m}$ is known as effective yield stress

Based on the aforesaid equation (12), the verification of the simulation model is carried out.

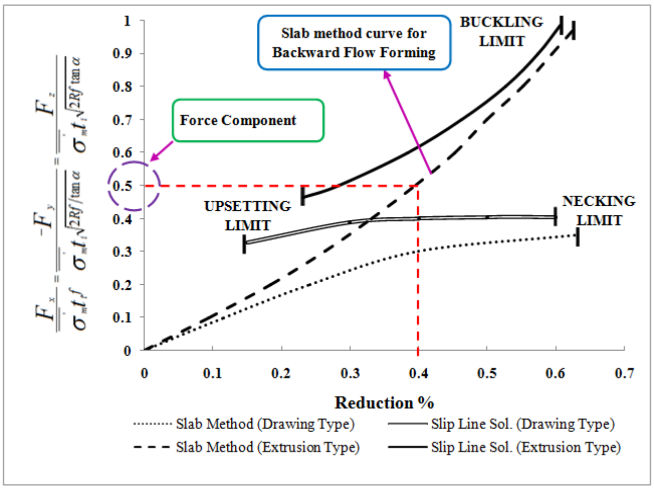

Fig. 4. Normalized force component selection (Redraw from Thomson et al. (1965))

All the material as well as geometrical properties kept same in order to maintain uniformity during analysis of both models. Thomson et al. (1965) proposed normalized force components as shown in figure 4 and according to that, these forces can be calculated theoretically.

It was also illustrated that the forward flow forming is identical with drawing and reverse flow forming is similar to extrusion. Thus considering the reverse approach in present study, extrusion curve was selected for the determination of normalized force component. In present case, reduction percentage is taken as 40% (Bhatt and Raval, 2016). Hence, corresponding force component has been obtained from figure 4. This force component is equated with Equation (12) to resolve the forces analytically.

The resultant of the three forces can be derived based on the equation given below,

$$F = \sqrt{(F_x^2 + F_y^2 + F_z^2} \qquad (14)$$

Figure 5 shows the comparison of forces between semi empirical and Thomson et al. (1965). It can be seen that axial force is highest followed by radial and circumferential force. Similar observation was reported by Bhatt and Raval (2016) for the individual forces. Thus, the axial force having more effect on resultant force compared to other two force components. The absolute percentage error was found as around 3.00 (axial force), 3.1554 (radial force), 9.3025 (circumferential force) and 3.2725 (resultant force). These variations in the results are due to certain assumptions made in the analytical model viz. plain stain condition, strains in hoop direction are taken as zero, friction between tool and workpiece is negligibly small etc.

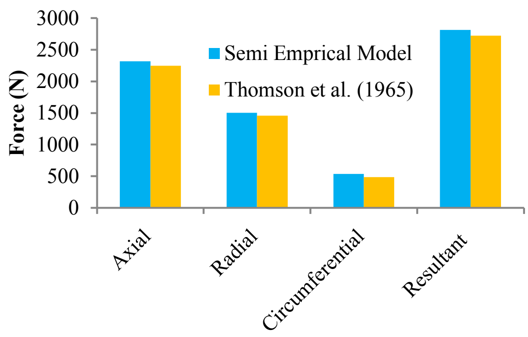

Fig. 5. Comparison of forces between semi empirical model and analytical model

In this way, a semi empirical model has been proposed and validated with the simulation and analytical model. The proposed model can be utilized to reduce the dependacy on high end computer hardwares and softwares along with exhaustive experimentations. Although, this model is not universal but the proposed methodology is good choice to look in depth for further issues during the process.

4. CONCLUSIONS

A dimensional analysis based semiempirical model has been developed to estimate the forces during the flow forming process. Based on the study, following closure can be drafted.

The predictability of the semiempirical model is more than 90% when compared with other two models.

The power indices and coefficients of the model indicate that the speed and forming depth along with material properties are having significant effect on forces.

In present study the model is developed for reverse approach but the the model can be used for forward approach. Despite the fact that, the deformation characteristics are quite different in both the approaches.

This could be used to unveil the issues like power consumption, surface integrity of the formed component etc.

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