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AN INVESTIGATION OF FORCES DURING FLOW FORMING PROCESS

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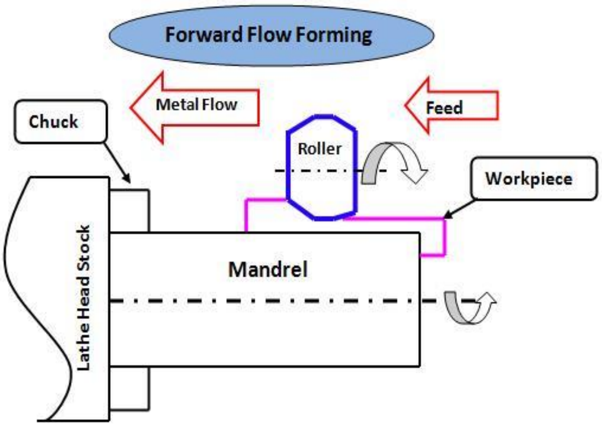
Abstract: Flow forming is gradually employed to produce high precision seamless components. It is mainly used in production of aerospace and defense components viz. rocket motor case, cartridge case, missile casing etc. The online monitoring of forces during the process is still difficult in commercial machines. The understanding of forces plays vital role in tooling design for various material and geometrical conditions. Hence, a simulation model is developed to estimate forces during the process. There are basically three forces encountered during the process i.e. axial, radial and circumferential. The material has been taken as Aluminum Alloy 6063 due to its versatile applications and certain advantages like excellent corrosion resistance, light weight, recyclable, ease of availability, cost effectiveness etc. Taguchi L27 design has been used to develop the simulation model as it is well developed design of experiment method. Three levels of six variables including three operating (rotational speed, axial feed and forming depth) and three geometrical (roller thickness, roller diameter and roller inclination) have been used during the study. The axial force has been observed to be highest followed by radial and circumferential force. Moreover, effect of rotational speed of roller has been discerned to be very significant on all three forces. Also, axial force has been perceived to be influenced by axial feed and roller diameter. It has been noticed that radial force was affected by forming depth and roller diameter. Further, a resultant force of these three forces has also been considered during the analysis. Axial feed, rotational speed, forming depth and roller diameter found to be prominent factors affecting resultant force.

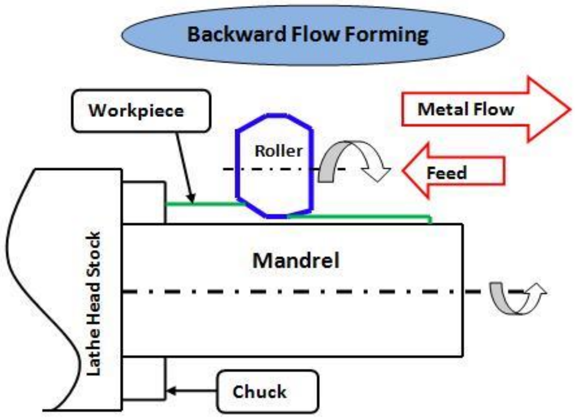
Key words: Investigation, Forces, Flow Forming, Taguchi, ABAQUS.

1. INTRODUCTION

Flow forming is non linear plastic deformation process with complex deformation behaviour. It is normally used to produce very high precision seamless components like rocket motor case, cartridge case, missile casing etc. for defense and aerospace industries. The process physics states that; a deformable tube is placed over the rigid mandrel and deformed by the rigid roller axially in the contact area. The inner diameter of the tube remains constant as the thickness reduces and length increases. There are basic two approaches used during the process i.e. forward and reverse (backward). In forward motion, the roller feed and material deformation are same direction as shown in Fig. 1(a) and, in backward motion, the roller feed and material deformation are opposite as per Fig. 1(b).



(a)



(b)

Fig.1. Schematic diagram of flwo forming (a) Forward (b) Backward

Earlier, Davidson et al. (2008) used four axis CNC flow forming machine with single roller tool and reported that the depth of cut is the most prominent parameter followed by speed and feed respectively.

Earlier in 2007, Davidson et al. studied the effect of process parameters on surface quality of tubes. They found that the starting dimension & starting heat treatment of preform, feed, speed and depth of cut have the significant effect on the flow forming. Wong et al (2005) used NC lathe with single roller tool to analyze the flow forming process. Flat and nosed roller used by them. They observed that nosed roller deforms material largely in axial direction and creates bulge. While flat faced roller produces radial flange ahead of it with increased diameter. Moreover, Rasoli et al (2012) did experimental study on flow forming using ultrasonic vibrations. The modal analysis is done by giving mandrel and roller ultrasonic vibrations. Based on the study, they found that inner surface quality of the tube can be improved by lower frequency of vibrations & material deformation and forces affected by higher frequency. Rajan et al (2002) done experimental studies on thin walled flow formed pressure vessels for critical high pressure applications has to consider different failure modes. The prediction of bursting pressure for thin walled tubes is done which was derived by Svensson (1958). Wang and Long (2011) studied four different roller profile during conventional metal spinning process. The roller profiles are linear, concave, convex and mixed concave & convex. They reported that the concave profile produces higher forces but higher wall thickness reduction can also be achieved. However, online force measurement is still difficult in commercial machines. Hence a simulation study is carried out to investigate forces during flow forming process.

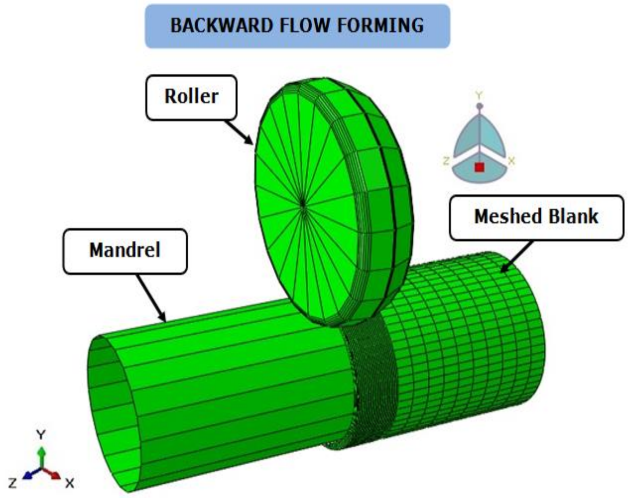
In the present study, Taguchi L27 design has been used. Six parameters including three operating (rotational speed, axial feed and forming depth) and three geometrical parameters (roller thickness, roller diameter, roller inclination) have been used. It was observed that rotational speed is the most significant factor during the process. Also, axial force is highest compared to radial and circumferential force.

2. MODELING AND ANALYSIS

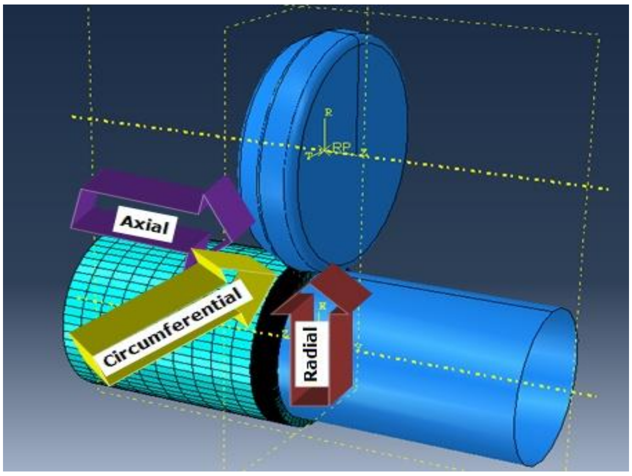
2.1 Modeling

Flow forming is influenced by many factors viz. process parameters, geometry of the tool and material properties. In the present work process parameters are taken as rotational speed of roller, axial feed and forming depth along with tooling parameters like roller diameter, roller thickness and roller inclination (with the work material). There are basically three forces are encountered during the process axial, radial and circumferential. Figure 2(a) and 2(b) shows the initial 3D model with meshed blank and the forces acting during the process respectively.

In the present study, the work material is taken as AA6063 due to its light weight, ease of availability, excellent corrosion resistance, effectiveness of cost and variety of applications in defense and aviation fields. Table 1 and Table 2 represent the chemical composition and physical properties of the work material respectively. The work material and tool parameters are given in Table 3.



(a)



(b)

Fig.2. (a) initial 3D model with meshed blank (b) forces acting during the process

Analytical rigid (undeformable) element used to model the roller and mandrel. It is not necessary to assign material properties and FE mesh to this element type. It will lead to reduction in computation cost, time and storage of memory. The tube is modeled using C3D8R, 8-node element. Finer mesh (0.5 mm) is adopted in the contact region. Boundary and initial contions have been applied considering roller motion viz. linear and angular velocities. Considering the inertia of roller, 100 mass scaling is applied to reduce computational time. It is assumed that the friction condition is follows by coloumb’s law i.e. friction between workpiece and mandrel is 0.1 & friction between work material and roller is 0.001. This friction model facilitates relative sliding between work material and roller.

Table 1. Chemical Composition of AA6063 (wt%) (Kim et al., 2013)

Element	Cu	Zn	Si	Mn	Mg	Fe
AA6063	0.069	0.1	0.34	0.013	0.42	0.1

Table 2. Physical Properties of AA6063 (Kim et al., 2013)

Material Density (Kg/m^3)	2700
Elastic Modulas (GPa)	68.9
Yield Strength (MPa)	48.3
Ultimate Strength (MPa)	89.6
Poisson's Ratio	0.33

Table 3. Work Material and tool parameters (Kim et al., 2013)

Parameter	Value
Work material	
Inside Diameter (mm)	35
Thickness (mm)	2.5
Starting Length (mm)	50
Roller	
Diameter (mm)	54
Angle of Attack (°)	25
Angle of Smoothing (°)	5
Percentage Reduction	40

2.2 Analysis

Taguchi method is well established design of experiment technique which is normally used to analyze complex and expensive experiments. Identification and optimization of optimal combination of different factors on desired response can be done by this method. The process and tooling parameters and their levels are given in the Table 4.

Table 4. Different Parameters with their levels

Factors	Level 1	Level 2	Level 3
Forming Depth (mm)	0.2	0.4	0.6
Rotational Speed (rpm)	30	60	90
Axial Feed (mm/s)	0.05	0.1	0.15
Roller Diameter (mm)	50	100	150
Roller Thickness(mm)	20	40	60
Roller Inclination (degree)	-15	0	15

During the analysis, L27 design was used, which requires only twenty seven simulations to be performed. The simulation analysis layout is given in Table 5.

Table 5. Simulation layout using L27 array

Simulation No.	Forming Depth: (FD) (mm)	Rotational Speed: (RS) (RPM)	Axial Feed: (AF) (mm/s)	Roller Diameter: (RD) (mm)	Roller Thickness: (RT) (mm)	Roller Inclination: (RI) (°)
1	0.2	30	0.05	50	20	-15
2	0.2	30	0.05	50	40	0
3	0.2	30	0.05	50	60	15
4	0.2	60	0.1	100	20	-15
5	0.2	60	0.1	100	40	0
6	0.2	60	0.1	100	60	15
7	0.2	90	0.15	150	20	-15
8	0.2	90	0.15	150	40	0
9	0.2	90	0.15	150	60	15
10	0.4	30	0.1	150	20	0
11	0.4	30	0.1	150	40	15
12	0.4	30	0.1	150	60	-15
13	0.4	60	0.15	50	20	0
14	0.4	60	0.15	50	40	15
15	0.4	60	0.15	50	60	-15
16	0.4	90	0.05	100	20	0
17	0.4	90	0.05	100	40	15
18	0.4	90	0.05	100	60	-15

19	0.6	30	0.15	100	20	15
20	0.6	30	0.15	100	40	-15
21	0.6	30	0.15	100	60	0
22	0.6	60	0.05	150	20	15
23	0.6	60	0.05	150	40	-15
24	0.6	60	0.05	150	60	0
25	0.6	90	0.1	50	20	15
26	0.6	90	0.1	50	40	-15
27	0.6	90	0.1	50	60	0

Now, the roller diameter and thickness can be defined as per the Fig. 3. Further, 15°, 0° and -15° are the inclinations of roller with the work material. Here, 15° indicates the roller inclination in clockwise direction (CCW), 0° indicates no inclination with work material and -15° indicates inclination in counter clockwise (CW) direction as shown in Fig. 4.

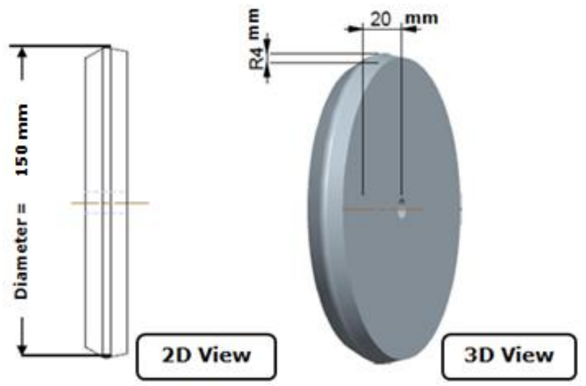


Fig.3. Roller diameter and thickness

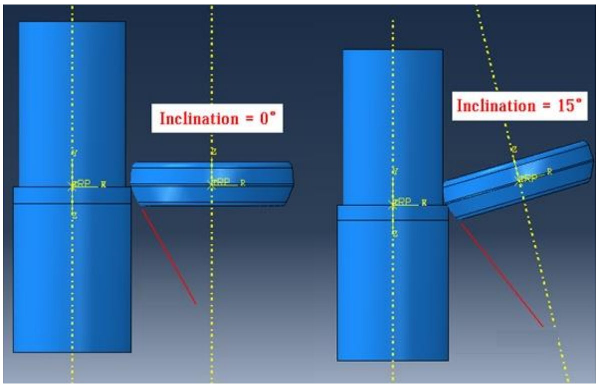


Fig.4. Roller inclination with workpiece

3. RESULTS AND DISCUSSION

Further, Taguchi et al. (2005) methodology depicts three types of quality characteristics i.e. smaller the better, nominal the better and larger the better. In present case, force(s) are considered as response parameter. Hence smaller the better quality characteristic has been adopted for S/N (signal to noise) ratio calculation. Taguchi stated that higher S/N ratio gives better performance. Therefore, better performance is the function of higher S/N ratio. The main effect plot for S/N ratio of axial, radial and circumferential forces are given in Fig. 5, 6 and 7 respectively.

It can be noted form Fig. 5 that the optimal performance for axial force can be achieved at 0.2 mm (level 1) forming depth, 30 rpm rotational speed (level1), 0.05 mm/s feed (level 1), 50 mm roller diamaeter (level 1), 60 mm roller thickness (level 3) and 0 degree (level 2) roller inclination. As can be seen from Fig. 6 that the optimal performance for radial force can be determined at 0.2 mm (level 1) forming depth, 30 rpm (level 1) rotational speed, 0.05 mm/s feed (level 1), 50 mm (level 1) roller diameter, 60 mm roller thickness (level 3), and 15 degree (CW) roller inclination with workpiece (level 3). Further it can be noticed from Fig. 7 that optimal performance of circumferential force can be achieved at 0.4 mm forming depth (level 2), 30 rpm rotational speed (level 1), 0.05 mm feed (level 1), 150 mm roller diameter (level 3), 60 mm roller thickness (level 3) and 0 degree roller inclination (level 2). It can be said that 30 rpm rotational speed and 0.05 mm/s axial feed give best performance result for all three forces. Whereas, 0.2 mm forming depth is quite good for optimal results of axial and radial force. Roller diameter was seem to be effecting parameter on axial and radial force, while other tool parameters i.e. roller thickness and roller inclination having nominal effect on all three forces.

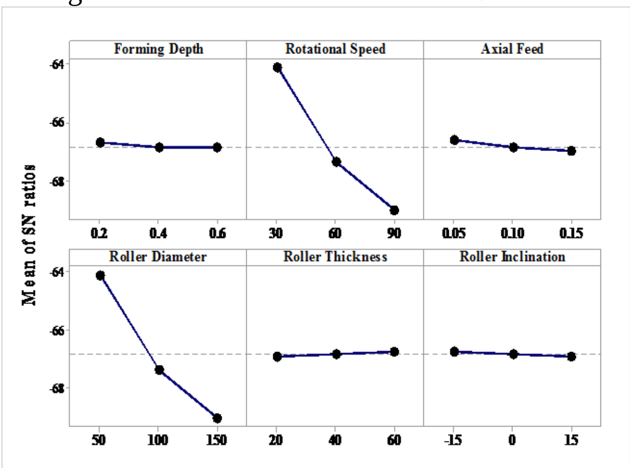


Fig.5. Graph of S/N ratio for Axial Force

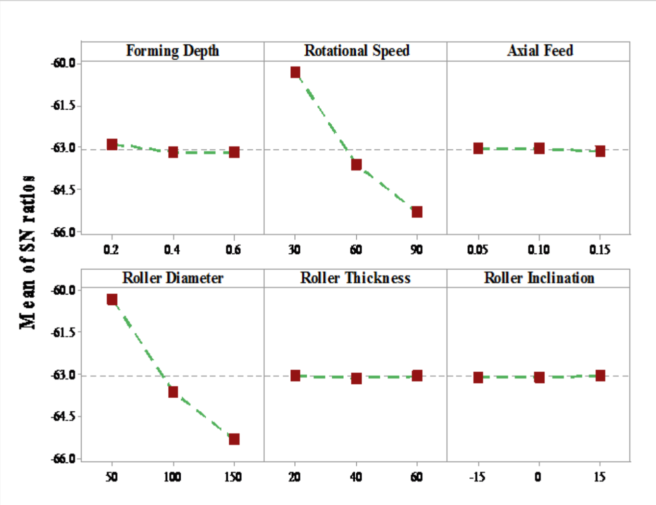


Fig.6. Graph of S/N ratio of Radial Force

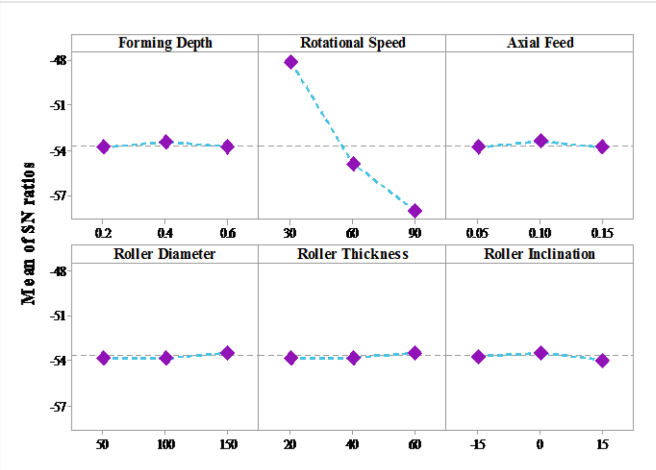


Fig.7. Graph of S/N ratio of Circumferential Force

Moreover, to understand the overall effect of forces on the roller during the process, a resultant force has considered as shown in Fig. 8. The resultant force of three forces (axial, radial and circumferential) has been determined based on the Equation (1).

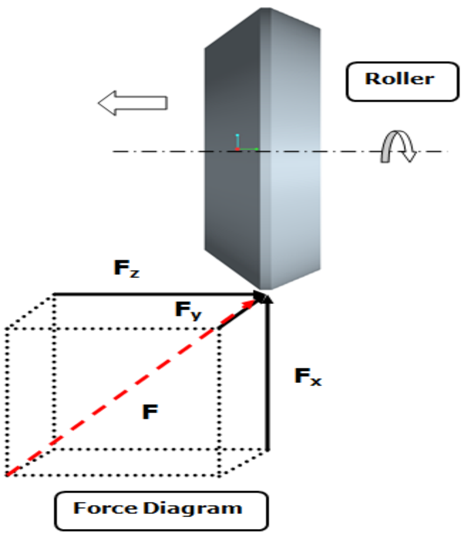


Fig.8. Resultant force Diagram

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

where, F_x = radial force, F_y = circumferential force, F_z = axial force and F = resultant force

The S/N ratio of the resultant force for optimal performance is given in Fig. 9. It can be noted that best performance of resultant force can be determined at 0.2 mm forming depth (level 1), 30 rpm rotational speed (level 1), 0.05 mm axial feed (level 1), 50 mm roller diameter (level 1), 60 mm roller thickness (level 3), and 0 degree roller inclination (level 2).

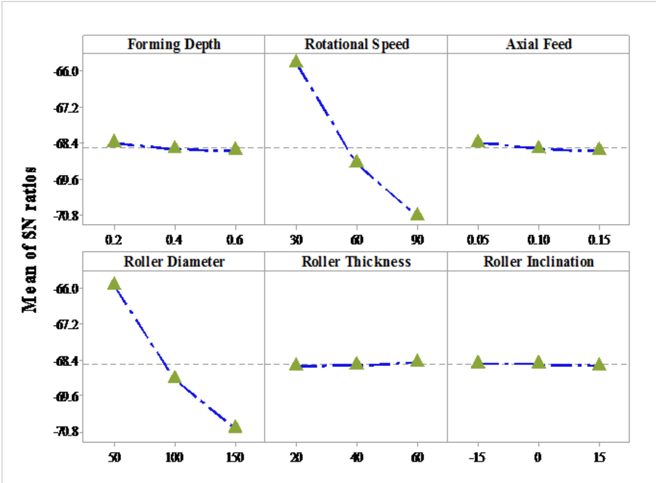


Fig.9. Graph of S/N ratio of Resultant force

From Fig. 9, it can be noticed that forming depth, rotational speed, axial feed and roller diameter having comprehensive effect on resultant force.

It can be said that, rotational speed increases, the forces increases. It is due to the higher compressive and shear forces encountered. Depth of forming also vital because too small depth may rise the spring back effect and too high depth may create material pile up. Axial feed value is also an important because as the axial feed increase beyond certain value it will generate build up that resists further deformation. Roller diameter will give the higher stiffness and rigidity during the deformation. Hence it is an important parameter too. But no significant effect was noticed for roller thickness and roller inclination. These are the parameters are quite important during conventional metal spinning process (Wang and Long, 2011) rather than flow forming.

The sample forces for the first simulation are given in Fig. 10. It can be seent hat the axial force is highest (1096.54 N) followed by radial force (689.39 N) and circumferentrial force (303.8 N).

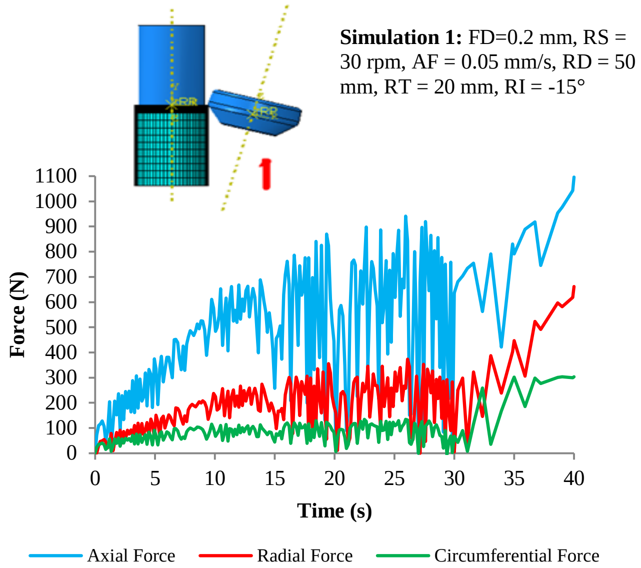


Fig.10. Forces variations for first simulation

The material is deformed axially, therefore compressive and shears forces acting during the process. Hence axial force is found to be highest. Radial force is intermediate of three forces. It is because of compressive forces due to forming depth applied by the roller. Circumferential force is least among all three forces due to the instantaneous contact between the roller and the work material.

It can be said that, rotational speed having major influence on all the three forces & resultant force also. It is noticed that resultant force is having effect of all three operating parameter and roller diameter.

4. CONCLUSIONS

In the present study, a simulation model is developed to study the effect of operating and tool parameters on forces during the process. Following are the broad conclusions based on the study.

-Rotational speed having highest influence on the forming forces.

-Forming depth and axial feed having marginal effect on the forming forces for the given dataset.

-Roller diameter having prominenet effect on forces compared to roller thickness and inclination.

-Resultant force is affected by rotational speed, axial feed forming depth and roller diameter.

-Axial force is highest for all the simulation due to shear and compressive forces during the process.

-Radial force is intermediate because of only compressive forces & circumferential force is least.

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