MULTIPLE PROCESS PARAMETER OPTIMIZATION OF FORWARD EXTRUSION PROCESS ON AA 2024

Anupama Francy Kothasiri¹, Srinivasa Rao Chalamalasetti², Gopalakrishnaiah Peteti³

¹Vishnu Institute of Technology, Bhimavaram, West Godavari, Andhra Pradesh, India, Pin code 534202

²Andhra University College of Engineering, Visakhapatnam, Andhra Pradesh, India. Pin code 530003

³PVP Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh, India. Pin code 520007

Corresponding author: Anupama Francy Kothasiri, kothasirianupama@gmail.com

Abstract: Extrusion is a simple metal forming process in which a block of metal is forced through a die orifice with a certain shape under high pressure. This extrusion process is influenced by many process parameters such as die angle (DA), ram speed (RS), coefficient of friction (COF), Extrusion ratio, Die land height, work piece diameter and length, material properties etc. In extrusion process, extrusion force is crucial parameter, the flow of metal and hence the extrusion force is significantly influenced by the above parameters which results in quality of the product. The present study numerically investigates the influence of major process parameters such as die angle, ram speed, coefficient of friction on the extrusion process. The AA2024 material is chosen as work piece material and the extrusion force and damage is considered as the output responses. The input process parameters are varied in three levels (Level - 1: 10° DA, 1.6mm/min RS, 0.06 COF; Level - 2: 20° DA, 3.2mm/min RS, 0.08 COF; Level - 3: 30° DA, 4.8mm/min RS, 0.01 COF). Numerical simulations are performed by using DEFORM 3D software. The simulations are conducted as per L_{27} orthogonal array. From the results it is observed that Increase of die angle, ram speed and coefficient of friction increases the extrusion force. The die angle has highest (86.45%) influence on the extrusion force, then after ram speed (6.60%). The coefficient of friction has insignificant influence (0.55%). It is also noticed that the damage is considerable after the 20° die angle. A multi parameter optimization is also done by using the Grey relation analysis by considering the equal weightage of extrusion force and damage. The optimum levels of input process parameters for the minimum extrusion force and damage is DA level 1, RS level 1, and COF level 3.

Key words: Aluminium 2024, Extrusion, Grey relational analysis, Die angle, Ram speed and Coefficient of Friction, ANOVA

1. INTRODUCTION

The automobile and aerospace industry needs the high precision components for proper alignment in the assembly operations. In general, these

components are prepared by various metal forming processes like extrusion (hot and cold), drawing, rolling, forging and stretch forming. Some of the processes are having their own operational constraints. For example, deep drawing used only for cup shaped products. Most of the components are bars and pipes of different cross sectional area. These bars and pipes are prepared by either in extrusion or drawing process. However, the extrusion process (passing bulk material through a die with a certain shape under high pressure) is widely used due to ease of operation. The extrusion process is of two types' cold extrusion and hot extrusion. The cold extrusion has an added advantage of improved mechanical properties than hot extrusion process.

The extrusion process seems to be simple but there is a number of parameters such as cross-sectional area, half die angle, ram speed, frictional conditions, extrusion ratio and material properties of the work piece influence the extrusion process (1). Several experimental and numerical studies are available in the open literature to understand the effect of the above parameters during the extrusion process. Effective die entrance angles are analysed through experiments for materials like Aluminium, Lead, Steel etc. to calculate minimum extrusion force (2-6). The extrusion force was increased till reaches a maximum die angle of 80° and then drops suddenly to zero at 110°, because of the extreme distortion that happens at larger die angles.

Coefficient of friction also plays a vital role in reducing the extrusion power in cold and hot extrusion method. A simple numerical approach is developed based on the lubrication approximation for obtaining the optimal die design. Taguchi L_9 orthogonal array is designed for the set of extrusion variables to simulate the experimental results with finite element analysis (7,8). Ram speed is also considered as an input parameter along with other parameters in the extrusion process to minimize

extrusion force. Extrusion power increased through the growing speed of punch since the greater punch speed origins complex strain rate besides larger flow stress. The impact of ram speed shows maximum effects on the extrusion force, hence ram speed was also considered as a significant parameter (9–12).

Nowadays, on improvement in the manufacturing growth simulation capability allows the designer to use computer aided design, which results in more accuracy, reduces design time, improves tolerance at each stage of the process (13–16). A basic numerical method for obtaining the optimal die configuration is developed based on the lubrication approximation. Taguchi L_9 orthogonal array is designed to replicate the experimental outcome with the collection of extrusion variables. The results revealed that die position, punch speed and friction values remain the most significant constraints. Several researchers attempted on optimization of process parameters associated with extrusion process so far. Most of the authors are mainly focussing mainly on minimisation extrusion force.

Venketesan et al (17) numerically studied the influence of die angle and extrusion ratio on extrusion force. The authors further optimized these parameters to obtain the minimum extrusion force. Similarly, Sadollah et al (12) numerically optimize the extrusion force by using the simulated annealing technique. Venkatesan and Narayanasamy (18) proposed a genetic algorithm to optimize the extrusion force by considering extrusion die ratio and die cone angle as influence parameters. Tapas et.al (13,14), conducted extrusion simulations for the material Aluminium 6061 alloy at the reduction ratios of 20:1 and 60:1 through round and square dies. Thella Babu rao et.al (19) numerically analysed the optimum process parameters (die angle, ram speed coefficient of friction) for extrusion process of the Aluminium 6061 alloy. The authors suggest an integrated FEA based approach to find the best process variables for the forward extrusion process. Optimization is done with the help of Taguchi method to minimize the extrusion load and temperature.

Farhoumand and Ebrahimi (20) numerically investigate the effect of geometrical parameters such as die corner radius and gap height as well as process condition such as friction between the work pieces and die for the forward extrusion. ABAQUS software was used for finite element simulations. The numerical method is validated with the help of experimental data in terms of form loadings, material flow, strain and hardness distribution in longitudinal cross-section of the product. The relation between hardness and strain value is compatible with the earlier work of the authors.

From the literature, it is observed that, the major process parameters such as die angle (DA), ram speed

(RS), and coefficient of friction (COF) significantly influences the extrusion output parameters. So, in the present work numerically analyse the influence of these parameters on extrusion process. The output extrusion process parameters considered in this study is extrusion force, damage factor. Multiple output parameter optimizations are also done by using the Grey Relation analysis by considering the equal weightage of extrusion force and damage factor.

2. MATERIALS AND METHODS

Figure 1 depicts the work flow chart followed in the present work and can be categorized mainly of three major steps. In the first step, work piece material selection and extrusion process influencing parameters are chosen. Initially the ranges of input process parameters are chosen then after levels are determined. In the second step, the simulation matrix is prepared based on the Taguchi method and simulation is done by using DEFORM 3D software. In the final step, based on the outcomes from the simulation. The influence of input process parameters is analysed. Optimization is done by using Taguchi and Grey relation algorithm. The subsequent section completely describes every step in detail.

Fig. 1. Research Workflow map

2.1. Selection of extrusion material and influence parameters

Work piece material used for the present simulation is Aluminium alloy AA2024. AA2024 is an economical material, having good physical properties (density 2.78 g/cm³, Young's Modulus is 73.1 GPA, tensile yield strength is 324 MPa and Poisson's ratio is 0.33), and

have a high surface finish and corrosion resistance [24]. Hence, AA2024 material is widely used in applications like navy ship-building, aircraft structures especially wing and fuselage structures, commercial & military aircraft etc. The detailed composition of the AA2024 material is presented in Table 1. The die and ram are made up of H13 steel. The H13 steel chemical composition and physical properties are presented in Table 2. The material H13 steel is used because of its high resistance to fatigue cracking.

The final extruded product's quality depends upon the parameters which influence the extrusion process. In general, the major parameters influencing the extrusion process is ram speed, die angle, billet diameter and length, coefficient of friction and extrusion ratio, material flow, die land height. However, optimization done by considering all these parameters leads to more complications. So, in the present work, basic parameters like Die Angle, Coefficient of Friction and Ram Speed are chosen in the present study.

2.2. Simulation matrix

Taguchi and Konishi (21) developed a method to do the optimization of multiple variables of multiple objectives. In this method, major influencing parameters play a vital role, which has been used to

achieve optimum levels of process parameters for the generation of quality characteristics. It employs an orthogonal array (OA) that has been used to learn the complete process parameters spacing with the least simulation possible. The levels of input factors selected for this study are listed in Table 3. In Taguchi optimization, S/N ratio stands the measure of quality characteristics and is estimated as follows. For smaller is better

$$\frac{S}{N} = \eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (1)$$

For larger is better

$$\frac{S}{N} = \eta = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \quad (2)$$

In the present work, S/N ratio is determined for extrusion force and damage factor and smaller-is-the-better criterion used to minimize both the extrusion force and damage factor. Table 3 provides the different levels of influencing parameters for the extrusion process and Table 4 shows the details of orthogonal array (OA) simulation matrix with the output response data.

Table 1. Element Composition of AA 2024 work piece [23]

Element	Fe	Cu	Zn	Si	Cr	Mg	Mn	Ti	Al
Composition (wt. %)	0.19	4.66	0.02	0.08	0.1	1.35	0.69	0.01	Bal

Table 2. Element Composition of H13steel used for die [24]

Chemical Composition										
Element	Cr	Mn	Mo	V	C	Ni	P	Cu	S	Si
Composition (%)	5.25	0.40	1.35	1.00	0.40	0.3	0.03	0.25	0.03	1.00
Physical properties										
Density	Melting point			Modulus of elasticity				Poisson's ratio		
7.80 g/cm ³	1427 °C			215 GPa				0.27 - 0.30		

Table 3. Input Factors and their levels

Factors	Representation	Level 1	Level 2	Level 3
Die Angle (deg)	DA	10	20	30
Ram Speed (mm/min)	RS	1.6	3.2	4.8
Coefficient of Friction	COF	0.06	0.08	0.1

Table 4. Design of L₂₇ orthogonal array and the simulation results

Exp. No	Die Angle	Ram Speed	Coefficient of Friction	Extrusion Force (KN)	Damage (%)
1	1	1	1	136.56	0.017
2	1	1	2	139.66	0.014
3	1	1	3	142.61	0.011
4	1	2	1	159.01	0.192
5	1	2	2	160.01	0.24
6	1	2	3	161.1	0.21
7	1	3	1	179.28	0.159
8	1	3	2	180.32	0.161
9	1	3	3	182.31	0.151
10	2	1	1	180.69	0.476

11	2	1	2	186.72	0.472
12	2	1	3	190.61	0.418
13	2	2	1	187.51	0.015
14	2	2	2	192.79	0.367
15	2	2	3	196.61	0.41
16	2	3	1	224.1	0.014
17	2	3	2	236.01	0.35
18	2	3	3	260.01	0.31
19	3	1	1	286.01	0.82
20	3	1	2	298.38	0.862
21	3	1	3	313.89	0.83
22	3	2	1	319.46	2.23
23	3	2	2	316.55	1.93
24	3	2	3	317.12	1.86
25	3	3	1	323.01	2.8
26	3	3	2	336.06	2.78
27	3	3	3	345.08	2.62

2.3. DEFORM 3D Simulation procedure

The present simulations are carried out in DEFORM-3D V6.1 software by using FEM. The DEFORM3D system consists of three major modules: pre-processor, processor and post-processor. Initially die, work piece and punch tool is modelled in CATIA software (Figure 2). The geometrical details of die, work piece and punch tool are depicted in table 5. In the pre-processor module, cold extrusion setup is done (Figure 3(a)). The post processor of extrusion process is as shown in Figure 3 (b & c). Meshing is done only for the billet with 140000 tetrahedral elements. The top die (ram) and bottom die considered as rigid materials. Coefficient of friction and ram movement direction is selected as boundary conditions for the cold extrusion. In the second module to do simulations, the Newton-Raphson method is used for the solution of the non-linear simulation equations. After the converging of each simulation, the extrusion force and damage data are noted for optimization purpose.

Figure 3 (b & c) depicts the effective stress distributions along with the load-time curve for the billet having 20° die angle. The extrusion process occurs with ram speed of 3.2 mm/min and 0.08 coefficient of friction considered at the interface of

die & work piece. It is observed that as ram pushes the material, the extrusion force is increases reaches a yield value that means the plastic deformation begins this can be observed in Figure 3(b) load time curve. Further the material start to flow from the die. The material undergoes compression and the maximum stress developed at the cross section changes (Figure 3(c)).

2.4. Grey Relation Method of Multi Objective Optimization

Grey relational method extensively used in multiple objective optimization problems (22). This method resolves complications in the inter relationship among multi variable optimization. The detailed procedure of the GRA optimization is discussed here. The foremost step is evaluation of S/N ratio from the simulation data starting from 0 to 1 by using equation 1. Then after Grey relation Normalization, Grey relational coefficient (GRC) and resolve of Grey relational grade (GRG) are to be evaluated. The standardized data of the extrusion force and damage factor from the simulation is used to estimate the grey relational normalization for the lower-the-better condition and is given in equation 3.

Fig. 2. Initial models of die, work piece and punch tool

Fig. 3. (a) work piece and die at its initial position (b) load& displacement (c) work piece after extrusion

Table 5. Geometrical details of die, work piece and ram

Parameter	Dimension
Work piece diameter	32mm
Work piece length	40mm
Top die height	20mm
Top die diameter	32mm
Inside diameter of the bottom die	32.2mm
Outside diameter of the bottom die	50mm
Die angles	10°, 20° & 30°

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{(\max y_i(k) - \min y_i(k))} \quad (3)$$

where $x_i(k)$ is the value after Grey relational generation, $\min y_i(k)$ is the smallest value of $y_i(k)$ for the k^{th} response, and $\max y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response.

After normalizing the new order, the resulting step is to find out the Grey relational coefficient $\varepsilon_i(k)$

$$\varepsilon_i(k) = \frac{\Delta_{\min} + \phi \Delta_{\max}}{\Delta_{oi}(k) + \phi \Delta_{\max}} \quad (4)$$

where $\Delta_{oi} = \|x_o(k) - x_i(k)\|$ = change of entire value $x_o(k)$ and $x_i(k)$; $\Delta_{\max}$ exhibit the value for maximum of Δ_{oi} , $\Delta_{\min}$ exhibits for minimum of Δ_{oi} and ϕ is individual coefficient. Grey relational is the average response of each grey relational coefficient. Grey relational grade γ_i can be estimated by equation 5 and is given below

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \varepsilon_i(k) \quad (5)$$

n stands for the number of process response.

3. RESULT AND DISCUSSION

The influence of process parameters (die angle, ram speed and coefficient of friction) on extrusion force and damage factor is numerically analysed. As explained earlier a total of 27 simulations are designed by using Taguchi L_{27} orthogonal array method. Simulations are performed in DEFORM-3D

software and the obtained results are used to optimize the extrusion process parameters.

3.1. Effect of process parameters on Extrusion Force

The influence of process parameters (die angle, ram speed and coefficient of friction) on minimum extrusion force is depicted in Figure 4 and the results are tabulated in Table 6. From Figure 4 it is observed that increase of die angle, ram speed and coefficient of friction increases the extrusion force, the increase in die angle increases the material flow within the die due to the increase of contact area. Hence, more force required to execute the extrusion process. If the ram speed increases, the billet temperature increases which results in more force required to extrude the material from the die. The influence of coefficient of friction is insignificant on extrusion force. From the ANOVA results it is observed that die angle (DA) has highest significance (86.45%) followed by ram speed (RS) (6.95%). Whereas the coefficient of friction (COF) (0.55%) has insignificant influence and same is depicted in Figure 4(b). The products of process parameters DA^2 has significant influence and for RS^2 have a less significant influence on extrusion force. The other parameters (COF^2 , $DA \times COF$, $DA \times RS$ & $RS \times COF$) influence on extrusion force is insignificant (Table 6). The combined influence of die angle, ram speed and coefficient of friction are easily analyses from the contour plots. Figure 5 (a, b and c) depicts the contour plots of extrusion by keeping the one parameter as constant and the other two parameters varying. It clearly observed from Figure 5 (a, b & c) the coefficient of friction influence with addition to either one of the process parameter (ram speed/die angle) on extrusion force is insignificant. The maximum of 0.08 % variations in extrusion force is noticed as coefficient of friction varies from 0.06 to 0.1. Whereas, the combined influence of die angle and ram speed parameters have a strong influence. From Figure 5, it observed that as die angle and ram speed decreases the minimum extrusion force is obtained. Therefore the optimized process parameters for minimum extrusion

force are 10° die angle, 1.6mm/min ram speed and 0.1 coefficient of friction.

The relationship between extrusion process parameters on extrusion force is modelled by a polynomial equation with the second order. The regression equations are obtained together with determination coefficients (R^2 adjacent-98.32 % and R^2 predicted -97.28 %). The extrusion force model (98.9%) is given by equation (6).

$$\text{Force(N)} = 173.1 - 6.10\text{DA} - 5.0\text{RS} - 397\text{COF} + 0.3257\text{DA} \times \text{DA} + 2.639\text{RS} \times \text{RS} + 1662\text{COF} \times \text{COF} - 0.090\text{DA} \times \text{RS} + 15.2\text{DA} \times \text{COF} + 44.7\text{RS} \times \text{COF} \quad (6)$$

The diagnostic checking of the model has been carried out by the examination of the residuals. Figure 6 shows the residual analysis data for the extrusion force. It is observed that the residuals fall on a straight line implying that the errors are normally distributed. The regression plot shows the goodness of the developed equation to forecast the extrusion force.

3.2. Effect of process parameters on Damage

The influence of process parameters (die angle, ram speed and coefficient of friction) on damage factor is depicted in Figure 7. The results are quoted in Table 7. It is observed that, process parameters increases the damage factor increases. This happened because of increase of extrusion force with increase of process parameters (die angle, ram speed and coefficient of friction) and damage increases. From the ANOVA results, it is observed that the contribution of die angle (DA) individually and its product (DA^2) is high (60.85% & 12.49%). The other process parameter ram speed (RS) contribution is significant (7.37%) and its product (RS^2) is less significant (0.23%) whereas coefficient of friction (COF) contribution individually and its product is insignificant. In the other interaction parameters the contribution of $\text{DA} \times \text{RS}$ (10.40%) is significant and $\text{DA} \times \text{COF}$ (0.111%) parameter contribution is less significant. the same can be observed in Table 7.

Figure 8 (a, b and c) depicts the contour plots of extrusion damage factor by keeping the one parameter as constant and the other two parameters varying. It clearly observed from Figure 8 by increasing die angle with one of the other parameters the damage factor increases and it is considerable after the 20° DA. Whereas, the ram speed and coefficient of friction influence on damage factor is insignificant. From the ANOVA the optimized process parameters for minimum damage factor is 10° die angle, 1.6 mm/min ram speed and 0.06 coefficient of friction.

The relationship between extrusion process parameters on damage factor is modelled by a polynomial equation with the second order. The regression equations are obtained together with

determination coefficients (R^2 adjacent-87.03% and R^2 predicted -78.18%). The damage factor model is given by equation (7). The proposed model predicts up to the accuracy of 91.5%.

$$\text{Damage(\%)} = 1.18 - 0.2546\text{DA} - 0.165\text{RS} - 21.4\text{COF} + 0.00679\text{DA} \times \text{DA} + 0.0357\text{RS} \times \text{RS} + 112\text{COF} \times \text{COF} + 0.027397\text{DA} \times \text{RS} + 0.227\text{DA} \times \text{COF} + 0.42\text{RS} \times \text{COF} \quad (7)$$

The diagnostic checking of the model has been carried out by the examination of the residuals. Figure 9 shows the residual analysis data for the damage factor. From that, it is observed that the residuals fall on a straight line implying that the errors are normally distributed. The regression plot shows the goodness of the developed equation to forecast the damage factor.

3.3. Effect of process parameters on Extrusion Force and Damage by using Gray relation analysis

The above section explains the influence of process parameters on extrusion force and damage factor individually. The Taguchi method is used to find the optimum parameters. In the present section, the influence of process parameters on extrusion force and damage factor analysed by using grey relation analysis. A direct standardization of the simulation results is used. The optimum output parameters are minimum extrusion force and damage factor. Every response measured since the simulation is regulated in the sort of 0 to 1 which is known as Grey relational generation. Table 8 indicates grey relational coefficients as well as grey relational grades of every simulation estimated by using equation 5. Among the 27 simulations, simulation 3 results have the maximum grey relation grade.

Figure 10 depicts the influence of considered parameters on GRG and the data from the GRG analysis is as shown in Table 9. Figure 11(a, b and c) depicts the influence of process parameters (die angle, ram speed and coefficient of friction) on GRG. From the individual analysis it is noticed that die angle and ram speed has major influence on extrusion force and damage. Whereas coefficient of friction has insignificant influence on extrusion force and minor influence on damage. So it is expected the die angle and ram speed has significant influence, the same depicts in the contour of DA & RS. For the other contours it shows the influence in the orientation of coefficient of friction is invariant. From the contour plot of DA & RS it is observed that the region between the low DA (10° – 15°), low RS (1.6 mm/min) has high GRG. Similarly GRG is high in the bounded region between the low DA & low COF (DA & COF) and low & high COF & low RS (COF & RS). The optimum values for the minimum extrusion force and damage factor (i.e. high GRG) are 10° DA, 1.6 mm/min RS and 0.01 COF.

A polynomial equation with the second order is modelled to estimate the GRG values. The regression equations are obtained together with determination coefficients (R^2 adjacent- 74.42% and R^2 predicted - 58.45%). The proposed model predicts up to the accuracy of 83.27 %. The model predicts moderate

accuracy is due to the unaccounted the other parameters in extrusion process.

$$\text{GRG}(\%) = 1.767 - 0.0292\text{DA} - 0.161\text{RS} - 10.2\text{COF} + 0.000102\text{DA} \times \text{DA} + 0.0113\text{RS} \times \text{RS} + 70.1\text{COF} \times \text{COF} + 0.00518\text{DA} \times \text{RS} + 0.010\text{DA} \times \text{COF} + 0.707\text{RS} \times \text{COF} \quad (8)$$

Table 6. Analysis of Variance for extrusion Force

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of cont	Remarks
Model	9	127201	14133	170.21	0.000	98.90	Significant
DA	1	111188	111188	1339.04	0.000	86.45	Significant
RS	1	8946	8946	102.31	0.001	6.96	Significant
COF	1	718	718	8.65	0.009	0.56	Significant
DA ²	1	6366	6366	76.67	0.000	4.95	Significant
RS ²	1	271	271	3.26	0.089	0.21	Insignificant
COF ²	1	3	3	0.03	0.860	0.01	Insignificant
DA×RS	1	25	25	0.3	0.593	0.02	Insignificant
DA×COF	1	111	111	1.33	0.264	0.09	Insignificant
RS×COF	1	25	25	0.3	0.594	0.02	Insignificant
Error	17	1412					
Total	26	128613

Fig.4. (a) Main effect plots of Extrusion force

Fig. 4 (b) Percentage contribution of parameters on extrusion force

Fig. 5. Contour Plot for Extrusion Force

Fig. 6. Residual plots for extrusion force

Fig. 7. Main effect plots of Damage and percentage contribution of parameters on extrusion damage

Table 7. Analysis of Variance for Damage

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of cont.	Remarks
Model	9	20.2761	2.2529	20.39	0.000	91.52	Significant
DA	1	13.4802	13.4802	122	0.000	60.85	Significant
RS	1	1.635	1.635	14.8	0.001	7.38	Significant
COF	1	0.0005	0.0005	0	0.946	0.01	Insignificant
DA ²	1	2.7667	2.7667	25.04	0.000	12.49	Significant
RS ²	1	0.05	0.05	0.45	0.51	0.23	Insignificant
COF ²	1	0.0121	0.0121	0.11	0.745	0.05	Insignificant
DA×RS	1	2.3048	2.3048	20.86	0.000	10.40	Significant
DA×COF	1	0.0247	0.0247	0.22	0.643	0.11	Insignificant
RS×COF	1	0.0022	0.0022	0.02	0.89	0.01	Insignificant
Error	17	1.8783	0.1105				
Total	26	22.1545

Fig. 8. Contour plots for extrusion damage factor

Fig. 9. Residual plots for the damage factor

Fig. 10. Main effect plots of GRG and percentage contribution of parameters on extrusion force and damage

Table 8. Normalized S/N ratio, Grey Relation Grade and Rank

Exp. No	S/N-Ratio		Normalized-S/N-Ratio		GRC		GRG	Rank
	Force (KN)	Damage (%)	Force (KN)	Damage (%)	Damage (%)	Force (KN)		
1	42.7065	-35.3910	1	0.92142	1	0.86418	0.93209	3
2	42.9014	-37.0774	0.97579	0.95646	0.95381	0.9199	0.93686	2
3	43.0830	-39.1721	0.95324	1	0.91447	1	0.95724	1
4	44.0285	-14.3340	0.83581	0.48378	0.7528	0.49202	0.62241	6
5	44.0829	-12.3958	0.82905	0.4435	0.74521	0.47326	0.60924	8
6	44.1419	-13.5556	0.82173	0.4676	0.73717	0.48431	0.61074	7
7	45.0706	-15.9721	0.70638	0.51782	0.63003	0.50907	0.56955	9
8	45.1209	-15.8635	0.70015	0.51557	0.62511	0.50791	0.56651	10
9	45.2162	-16.4205	0.68831	0.52714	0.616	0.51395	0.56497	11
10	45.1387	-6.4479	0.69793	0.31988	0.62339	0.42368	0.52354	12
11	45.4238	-6.5212	0.66252	0.3214	0.59703	0.42423	0.51063	13
12	45.6029	-7.5765	0.64028	0.34333	0.58158	0.43228	0.50693	15
13	45.4605	-36.4782	0.65797	0.94401	0.5938	0.8993	0.74655	4
14	45.7017	-8.7067	0.62801	0.36682	0.5734	0.44124	0.50732	14
15	45.8721	-7.7443	0.60685	0.34682	0.55981	0.43358	0.4967	16
16	47.0088	-37.0774	0.46567	0.95646	0.48341	0.9199	0.70165	5
17	47.4586	-9.1186	0.40981	0.37539	0.45864	0.4446	0.45162	17
18	48.2998	-10.1728	0.30534	0.39729	0.41853	0.45343	0.43598	18
19	49.1276	-1.7237	0.20253	0.22169	0.38537	0.39114	0.38825	19
20	49.4954	-1.2899	0.15686	0.21268	0.37226	0.3884	0.38033	20
21	49.9355	-1.6184	0.10219	0.21951	0.3577	0.39047	0.37409	21
22	50.0883	6.9661	0.08322	0.04109	0.35291	0.34272	0.34782	24
23	50.0088	5.7111	0.09309	0.06717	0.35539	0.34896	0.35217	23
24	50.0245	5.3903	0.09115	0.07384	0.3549	0.35059	0.35275	22
25	50.1843	8.9432	0.0713	0	0.34997	0.33333	0.34165	25
26	50.5283	8.8809	0.02857	0.00129	0.33981	0.33362	0.33671	26
27	50.7584	8.3660	0	0.01199	0.33333	0.33602	0.33468	27

Table 9. Analysis of Variance for GRA

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% of cont	Remarks
Model	9	0.75139	0.08349	9.4	0.000	83.27	Significant
DA	1	0.55516	0.55516	62.53	0.000	61.53	Significant
RS	1	0.08089	0.08089	9.11	0.008	8.96	Significant
COF	1	0.01617	0.01617	1.82	0.195	1.79	Insignificant
DA ²	1	0.00063	0.00063	0.07	0.794	0.07	Insignificant
RS ²	1	0.00504	0.00504	0.57	0.461	0.56	Insignificant
COF ²	1	0.00472	0.00472	0.53	0.476	0.52	Insignificant
DA×RS	1	0.08259	0.08259	9.3	0.007	9.15	Insignificant
DA×COF	1	5.3E-05	5.3E-05	0.01	0.94	0.01	Insignificant
RS×COF	1	0.00615	0.00615	0.69	0.471	0.68	Insignificant
Error	17	0.15092	0.00888				
Total	26	0.90231

Fig. 11. Contour plots for GRG

Fig.12. Residual plots for the GRG

Fig. 13. Variation of experimental data and the simulation data

3.4. Validation

The simulation model used in the present study is validated with the experimental data of the Z Jurkovic et al. [15]. Experiments are conducted by varying the DA, coefficient of friction and logarithmic strain. Figure 13 depicts the variation of experimental data and the simulation data in terms of extrusion force. It clearly observed that present used simulation model/procedure closely predicts the extrusion force. The average deviation observed is less than 5%.

4. CONCLUSIONS

In the present study, the influence of process parameters (Die Angle, Ram Speed and Coefficient of Friction) on cold extrusion process is numerically analysed. The extrusion process is performed for the AA 2024 material and the extrusion force and damage factor are considered as responses. Initially, the process parameters influence is studied individually. Then after multi objective optimization is done by using Taguchi Grey relation analysis. The ANOVA model proposed here describes the contribution of extrusion process parameters on the output responses. The main conclusions of the current study are as follows:

- The extrusion force and damage increases with the increase of process parameters.
- From the Individual ANOVA analysis, it is observed that the DA & RS has significant influence on extrusion force and damage. Whereas COF influence on extrusion force is insignificant but on the damage is significant.
- Grey relation analysis done for the multi optimization of extrusion force and damage factor. The optimum process parameters obtained for GRG are 10° die angle, 1.6 mm/min ram speed and 0.06 COF. COF influence on extrusion force and damage is significant.

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