7th Bangladesh Conference on Industrial Engineering and Operations Management
December 21-22, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/BA07.20240086
Published: December 21, 2024

Finite Element Simulation of Alloyed Steel (20MnCr5) in Extrusion Process Using Deform 3D Software

Rotan Kumar Saha[1], Md. Touhiduzzaman[1], Md. Mamun[2], Md. Tareque Hasan[1], Safayet Hossain[1], Md. Rafiqul Islam[1], Md. Nazmul Hasan[1], Tuhin Hosen[1], Md. Rahat Bhuiyan[1]
[1]Department of Industrial and Production Engineering, Dhaka University of Engineering & Technology, Gazipur, Gazipur-1707, Bangladesh
[2] Department of Mechanical Engineering, Dhaka University of Engineering & Technology, Gazipur, Gazipur-1707, Bangladesh

rotansaha@duet.ac.bd, touhid@duet.ac.bd, mamun193016@gmail.com, tareque.me2019@gmail.com, safayetridu@gmail.com, rafiqul90000@gmail.com, nazmulhasan207015@gmail.com, tuhinhosenipe@gmail.com, brahat9880@gmail.com

Abstract

This study focuses on optimizing input process parameters for the extrusion of alloyed steel (20MnCr5) using finite element simulation via DEFORM-3D software and the Taguchi method. The selection of appropriate process parameters is critical to minimize extrusion force, particularly when different material sets are involved. The research examines key parameters such as billet material properties, workpiece geometry, die angle, coefficient of friction, logarithmic strain, ram speed, and die length. Through DEFORM 3D simulation, the minimum extrusion force is predicted, and optimal process parameters are identified using Taguchi analysis. The regression analysis identified optimal conditions with a coefficient of friction at 0.08, die angle at 20°, and ram velocity at 1.5 mm/s, resulting in an extrusion force of 556291KN. ANOVA results indicate that die angle is the most influential factor, contributing 43.45% to the variation in extrusion force. Using an L27 (3^3) orthogonal array, the experiments were analyzed via MINITAB software. The analysis of extrusion speed's effect on temperature revealed a maximum die temperature of 600°C and billet temperature of 1030°C at ram speeds between 1-2 mm/s. Additionally, the temperature-stress relationship indicated the highest stress value of 1000 MPa at 20°C with 0.7% strain, while the lowest stress of 90 MPa occurred at 1050°C with 0% strain. The findings demonstrate the significant impact of optimized parameters on reducing extrusion force, enhancing process efficiency.

Keywords
Extrusion process, Optimization, Taguchi analysis, Finite element simulation, DEFORM-3D software

1. Introduction
The extrusion process is one of the industry's most crucial metal-forming process and performs complex assembly operations by forcing the product through a die. Alloy steels such as 20MnCr5 are widely used in the automotive and heavy machinery sectors and encounter significant problems during extrusion due to their high strength and hardness. 20MnCr5 is a low alloy hardened steel material with excellent wear resistance and toughness, but this material provides higher extrusion strength by preventing deformation during extrusion. Finite Element Analysis (FEA), primarily through DEFORM 3D software, provides a powerful platform for simulating complex extrusion processes. This method allows for a detailed investigation of flow properties, stress distribution, and strain during solid materials such as 20MnCr5 extrusion. Important extrusion parameters affecting strength include dead angle, friction coefficient, logarithmic strain, and perforation speed (Valberg, 2010). To improve this disadvantage, the Taguchi method, a valuable tool for experimental design, was used. The Taguchi method helps to determine the best parameters that minimize the extrusion force using a small number of tests. DEFORM 3D's FEA, combined with post-processing

analysis using the Taguchi method, provides a way to improve the metal extrusion process (Silva et al., 2014). The extrusion of 20MnCr5 often comes with significant problems, such as exceptionally high extrusion pressure, which can lead to inefficiency, increased material wear, and the possibility of end product failure. Reducing extrusion pressure is essential for productivity and lower production costs. Input parameters such as die angle, coefficient of friction, logarithmic strain, and screw speed play an important role in determining the performance of the extrusion process. However, the complex interactions between these variables make it difficult to predict their effects on extrusion forces using traditional methods. This difference in understanding highlights the need for better analytical methods. The extrusion process can be studied in detail using finite element analysis (FEA) with DEFORM 3D software. This research contributes to materials engineering and manufacturing, particularly in optimizing the extrusion process of alloy steels. The main contributions include the development of 20MnCr5 extrusion modeling using DEFORM 3D to improve the understanding of material behavior under extrusion conditions. Key inputs such as coefficient of friction, die angle and extrusion speed are analyzed and optimized to reduce the required force.

1.1 Objectives

The primary objective of this research is to optimize the extrusion process parameters for 20MnCr5 alloy steel by integrating DEFORM 3D finite element simulations with the Taguchi method. The study systematically investigates the mechanical behavior of 20MnCr5 steel during extrusion, focusing on critical parameters such as die angle, coefficient of friction, ram velocity, and logarithmic strain to evaluate their influence on extrusion force and material flow. A robust simulation model is developed to analyze these factors comprehensively, enabling the identification of optimal conditions through Taguchi analysis to minimize extrusion force and enhance process efficiency. Furthermore, the accuracy of the simulation results will be rigorously validated against established literature, ensuring the reliability and practical applicability of the findings.

2. Literature Review

The extrusion process has attracted interest in materials engineering, especially for optimizing products and understanding product behavior under harsh conditions. Subramanian and Palani Radja (Subramanian, Palaniradja, & Exploration, 2018) found different properties between the extruded rod's center and sides. Hoida et al. (Hojda, Sturm, Terhorst, Klocke, & Hirt, 2017) developed a 3D finite element model including thermo-mechanical and electric field elements using Abaqus/Standard to simulate hybrid forward extrusion. Zhou et al. (W. Zhou, Shi, Lin, & Manufacture, 2018) introduced the difference in external extrusion (DVSE) to predict the curve from the measured model. The extrusion of AA6061-5% SiCp composite was studied by Akhgar et al. (Akhgar, Mirjalili, Serajzadeh, & Applications, 2011) regarding the thermomechanical behavior of the mixture under hot extrusion Purbahari et al. (Pourbahari, Mirzadeh, Emamy, & Roumina, 2018) on the use of dynamic recrystallization to increase grain size. Tamasby et al. (Tahmasbi & Mahmoodi, 2018) used friction stir extrusion (FSE) to study interfacial bonding. Yu and Zhao (Yu & Zhao, 2018) identified nanostructures in the source during die extrusion. Sahu et al. (Sahu, Das, Dash, & Routara, 2018) measured the extrusion load variation for porous geometry. (Khosravifard, Ebrahimi, & Design, 2010) performed a detailed analysis of rod extrusion to evaluate the impact of the technology. Ebrahimi et al. (Ebrahimi, Gholipour, Djavanroodi, & A, 2016) investigated severe plastic deformation via balanced channel forward extrusion. Finally, Parvizian et al. (Parvizian, Schneidt, Svendsen, & Mahnken, 2010) used DEFORM 3D to simulate hot metal design to solve significant deformation problems.

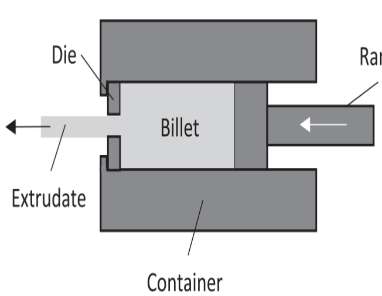


Figure 1. Schematic drawing of direct extrusion

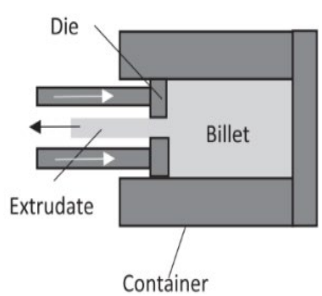


Figure 2. Schematic drawing of indirect extrusion

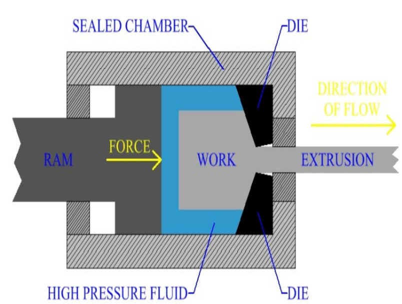


Figure 3. Schematic drawing of hydraulic extrusion

Figure 1 shows direct extrusion, where the blank is forced through the die like a pressure stamping process that produces a standard product. Figure 2 shows indirect extrusion, where the die moves to a fixed position, reducing friction between the blank and the box. Figure 3 shows hydraulic extrusion, a process that uses hydraulic pressure to push material through a die and is ideal for materials that require tight control.

The extrusion process is widely used in metal production and is affected by many factors, such as the shape of the work, die design, friction, stamping speed, temperature, and material, all of which affect the quality of the final product and the energy efficiency of the product (Karayel, 2008). Extrusion optimization has gained knowledge from many methods such as modeling, simulation, computer, and artificial intelligence to improve the accuracy of tool design and extend the working life (Valberg, 2010). Yanran et al. analyzed the stable deformation during extrusion and optimized the die angle to reduce the deformation forces, which shows a good relationship between the experimental and simulation results. Finite element method (FEM) simulations have emerged as the best alternative to predict essential factors such as extrusion loads and crack reduction, thereby increasing the accuracy of all process variations. Pathak and Ramakrishnan used evolutionary algorithms and dynamic object models to optimize the strain rate and punching speed and validated the result with genetic algorithms (KK & sciences, 2007). Azad and Noorani increased the forward extrusion efficiency by predicting the change in load and stress while changing the die angle (Noorani-Azad, Bakhshi-Jooybari, Hosseinipour, & Gorji, 2005) a recent study by Jurk et al. Focusing on reducing the extrusion pressure through a combination of optimization techniques, including the Taguchi method, has yielded promising results in alloy steel extrusion (Jurkovic, Jurkovic, Buljan, & engineering, 2006),(Jurković, Brezočnik, Grizelj, & Mandić, 2009). This paper uses the advanced simulation technology of Deform 3D software to model the hot extrusion process, emphasizing the role of accurate simulation in predicting the material and optimizing the process to achieve good quality (Schikorra, Donati, Tomesani, & Tekkaya, 2008). Simulations effectively detect temperature changes, which are essential for evaluating material behavior at high temperatures by defining material properties, geometric configurations, and boundary conditions (J. Zhou, Li, & Duszczyk, 2003). This approach can identify and reduce potential problems such as irregular deformation and high stress, thus improving the extrusion process and die design (Chaudhari, Andhale, Patil, & Engineering, 2012).

This study uniquely optimizes the extrusion process parameters for 20MnCr5 alloy steel by addressing critical gaps in existing research. Unlike previous works that focus on individual factors such as die angle, friction, and ram speed, this research uses the Taguchi method to evaluate their combined effects comprehensively. Additionally, it investigates the influence of logarithmic strain on extrusion force reduction, a novel aspect not explored in prior studies. By leveraging DEFORM 3D simulation software for precise optimization, this study provides a more integrated approach, enhancing the understanding of 20MnCr5 steel's extrusion behavior and offering valuable insights for process efficiency.

3. Methodology

This research employs a systematic methodology to optimize the extrusion process of 20MnCr5 alloy steel using DEFORM 3D software for simulation and analysis. The process begins with detailed modeling, including geometry setup, mesh generation, and defining material properties like stress, strain, and thermal characteristics. Critical extrusion parameters such as die angle, ram speed, temperature gradient, and coefficient of friction are iteratively adjusted to achieve optimal performance. Figure 4 shows the comprehensive outline of the methodology used in this study. The simulation examines the impact of these parameters on material flow, temperature variations, and extrusion forces, enabling analysis of deformation patterns, surface finish, and potential defects. The study uniquely incorporates logarithmic strain to characterize the material behavior under extreme deformation, offering insights into the effects of various factors such as friction and die wear on extrusion efficiency and product quality. By systematically optimizing these parameters, the research aims to enhance the process's overall efficiency and reduce extrusion force, ultimately improving the quality of extruded products.

3.1 Simulation Setup

The extrusion process was simulated using DEFORM 3D software, known for its design capabilities in metalworking. The simulation involves transferring the geometry of the extrusion die and the raw material to ensure that the die quality represents the intended profile. Critical properties for the cavities were defined, including the elastic modulus and yield strength. Mesh generation was performed to ensure sufficient detail was captured during the extrusion process, and mesh refinement was performed using tools available in DEFORM 3D. Use boundary conditions to represent the die's movement and the cavity's confinement. The contact between the die and the workpiece is defined, including the friction coefficient and the contact algorithm. Depending on the material, select a suitable model, such as rigid plastic or elastoplastic. Once the simulation is complete, post-processing tools in DEFORM 3D help define deformation, stress, and distribution. The information obtained from this analysis suggests redesigns that will improve the extrusion process and ultimately improve product quality and performance.

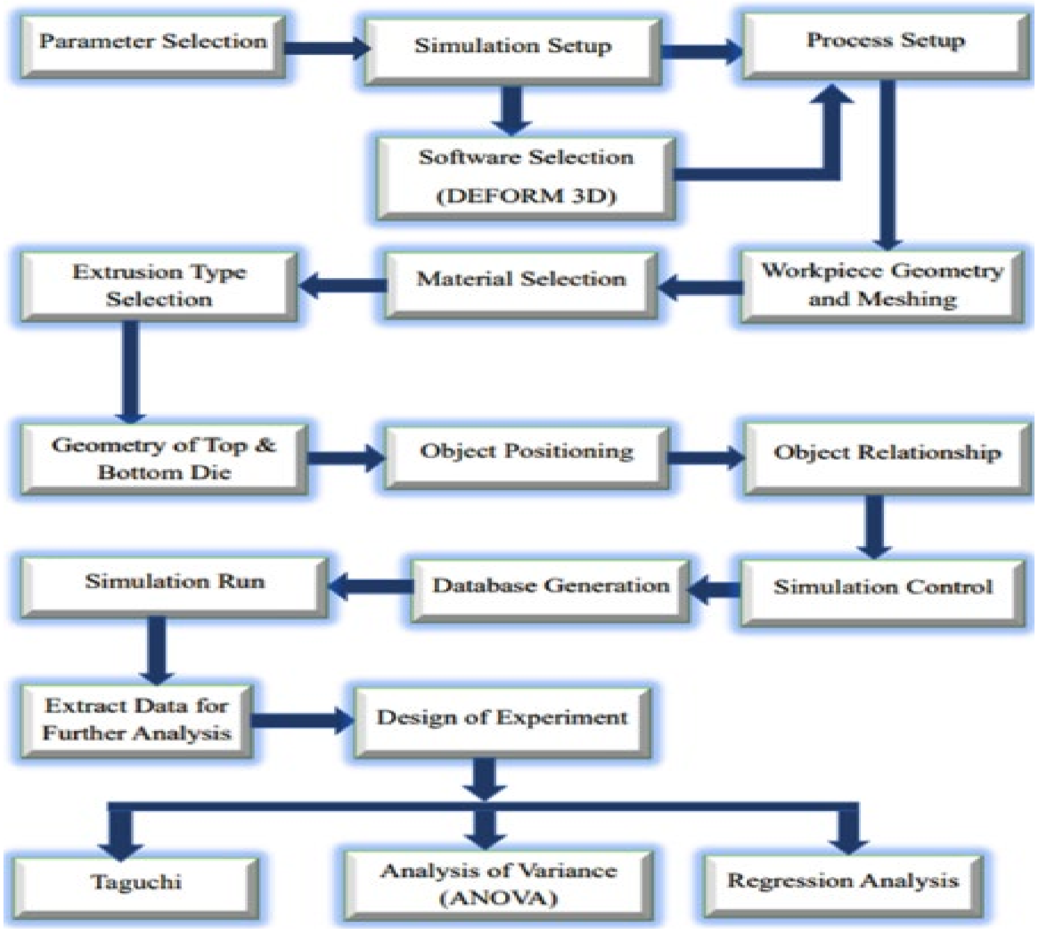


Figure 4. Overview of the research methodology

3.2 Process Setup

In DEFORM-3D, defining the workpiece geometry involves creating or importing the surface shape, capturing its dimensions and material properties accurately. The next step is mesh generation, where the workpiece is subdivided into finite elements to model its deformation behavior. Depending on the geometry's complexity and desired simulation accuracy, structured or unstructured meshes may be used. This study utilized mesh optimization techniques to refine critical areas, enhancing the simulation's precision. A total of 32,000 mesh elements were created to ensure accurate analysis. The material properties, including stress flow and thermal characteristics, were selected using DEFORM-3D's built-in library. Figure 5 is showing the Workpiece geometry creation and meshing process. For this simulation, 20MnCr5 alloy steel was chosen based on its mechanical attributes reported in the literature. The process of creating the workpiece geometry, meshing, and selecting material properties is illustrated in Figures 5 and 6, providing a comprehensive foundation for the extrusion process simulation.

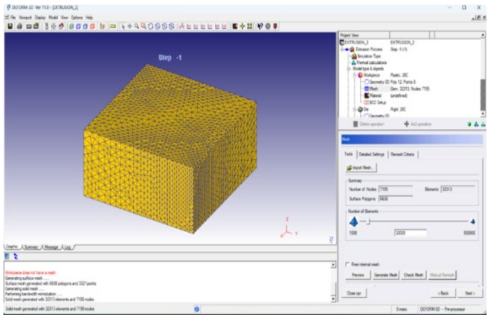


Figure 5. Creating workpiece geometry and meshing

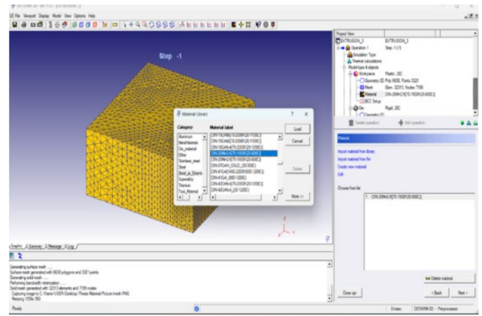


Figure 6. Material selection in DEFORM-3D software

3.3 Geometry of Top & Bottom Die

The upper die acts as a RAM or punch during the extrusion process, including rapid extrusion. Its dimensions are 500 mm in diameter and 230 mm in height. Figure 7 illustrates the top die, also known as the ram or punch. The lower die plays a vital role in forming the molten material into the required part of the joint. This die ensures consistency and accuracy in the size and finish of the extruded product.

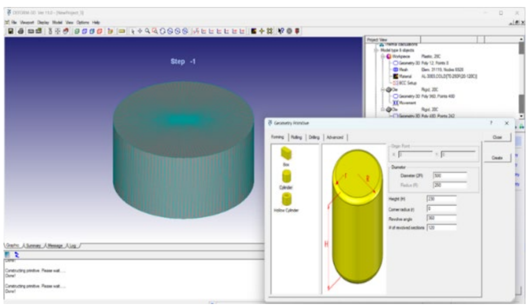


Figure 7. Top die (Ram or Punch)

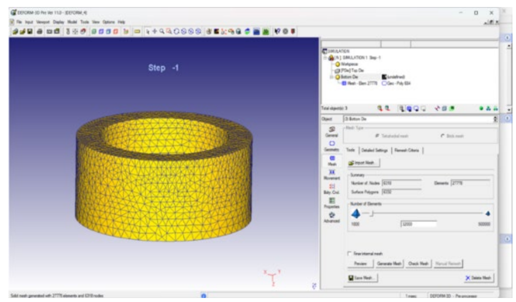


Figure 8. Bottom die

Figure 8 illustrates the bottom die used in the simulation. It also controls the material flow to prevent defects such as voids, warpages, or unevenness. Proper die design and maintenance are essential to produce consistent, high-quality extrusion products. The lower die has an outer diameter of 260 mm, an inner diameter of 150 mm, and a height of 100 mm. In DEFORM 3D, the object placed for extrusion will align the original object geometry with the desired configuration of the extrusion die in the simulation domain. The initial geometry is placed to represent the starting point before the extrusion begins. Pan, rotate, or zoom adjustments can be made for accuracy. Figure 9 illustrates the workpiece along with the top and bottom dies. Figure 10 illustrates the relationship among the workpiece, top die, and bottom die. By properly defining and modeling inter-object relations in Deform 3D, we can simulate the extrusion process with greater accuracy and understand how different factors affect the quality and behavior of the extruded material.

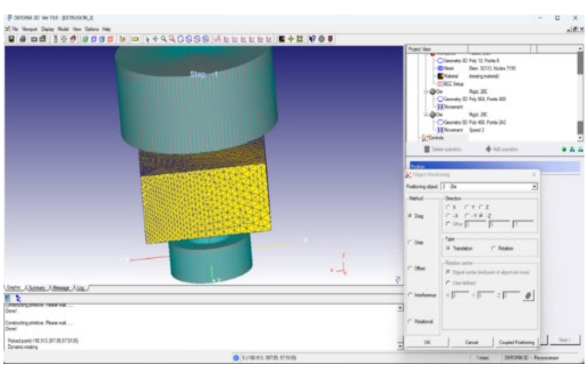


Figure 9. Object (Workpiece, Top and Bottom die) positioning

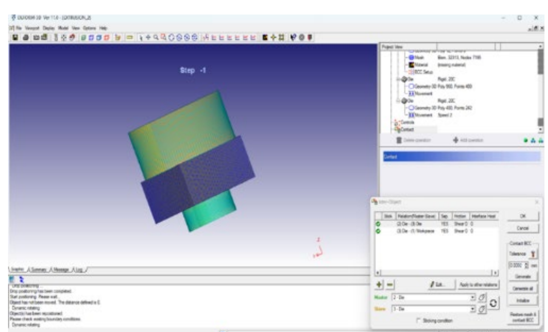


Figure 10. Inter object relationship between workpiece, top, and bottom die

3.4 Simulation Run

After entering all the information for preprocessing in the Deform 3D software, it will be ready for simulation. After saving the data and clicking the run button, the simulation will start. After the simulation process is completed, we will be able to analyze the data for each step. From there, we can take the necessary data. Figure 11 shows the data extraction at specific points or regions for detailed analysis and comparison using DEFORM 3D simulation software. DEFORM 3D allows users to extract adequate stress data at specific points or regions for further analysis or comparison. This data can be exported for statistical analysis, generated as plots, or incorporated into reports and presentations. The following table is constructed based on the data in Table 1, where each single value is combined with all other values. Then the simulation is run with these values. The extrusion force is measured during the test by controlling different levels. Variance analysis is used to determine the extrusion values that are not related to the extrusion strength. A linear model was adopted using the extrusion force as the response parameter, and the confidence level was 95%.

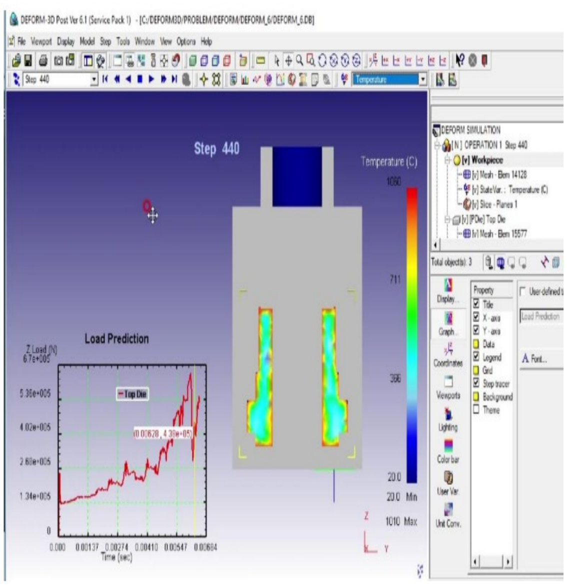


Figure 11. Extract data at specific points or regions for further analysis or comparison by DEFORM 3D simulation software

Table 1. Orthogonal design array

Serial No	Logarithmic Strain	Die angle	Coefficient of friction	Extrusion velocity	Simulatio Extrusion f (KN)
1	0.3080	20	0.08	1	544000
2	0.3080	30	0.1	1.5	579541
3	0.3080	40	0.12	2	566520
4	0.6040	20	0.08	1	532099
5	0.6040	30	0.1	1.5	582427
6	0.6040	40	0.12	2	581020
7	0.9040	20	0.08	1	549370
8	0.9040	30	0.1	1.5	579304
9	0.9040	40	0.12	2	611159
10	0.3080	20	0.12	1	542067
11	0.3080	30	0.1	1.5	588558
12	0.3080	40	0.08	2	590642
13	0.6040	20	0.12	1	551123
14	0.6040	30	0.1	1.5	589347
15	0.6040	40	0.08	2	591944
16	0.9040	20	0.12	1	597364
17	0.9040	30	0.1	1.5	586415
18	0.9040	40	0.08	2	614151
19	0.3080	20	0.1	1	546010
20	0.3080	30	0.08	1.5	589541
21	0.3080	40	0.12	2	586701
22	0.6040	20	0.1	1	551065
23	0.6040	30	0.08	1.5	591362
24	0.6040	40	0.12	2	590013
25	0.9040	20	0.01	1	551397
26	0.9040	30	0.08	1.5	586432
27	0.9040	40	0.12	2	602225

4. Results and Discussion

4.1 Data Comparison

Validating finite element simulation results with experimental data is essential to ensure accuracy. This study utilized the experimental data from Ramesh et al. (2013) to compare and verify the extrusion forces predicted by the DEFORM 3D simulation. Table 4.1 presents a comparison between simulated extrusion forces and those obtained experimentally. Although the general trend of extrusion force from the DEFORM 3D simulation closely matched the experimental findings, some discrepancies were noted. These variations are common and primarily stem from the simplifications made in the finite element model, which might not capture all the influencing factors of the actual machining process. Despite these minor differences, the simulated results were sufficiently close to the experimental data, allowing for reliable forecasting of machining responses across all test conditions. Subsequently, the results facilitated further optimization using Taguchi and ANOVA methods to identify optimal extrusion parameters. The comparative analysis for 20MnCr5 steel extrusion forces is detailed in Table 2.

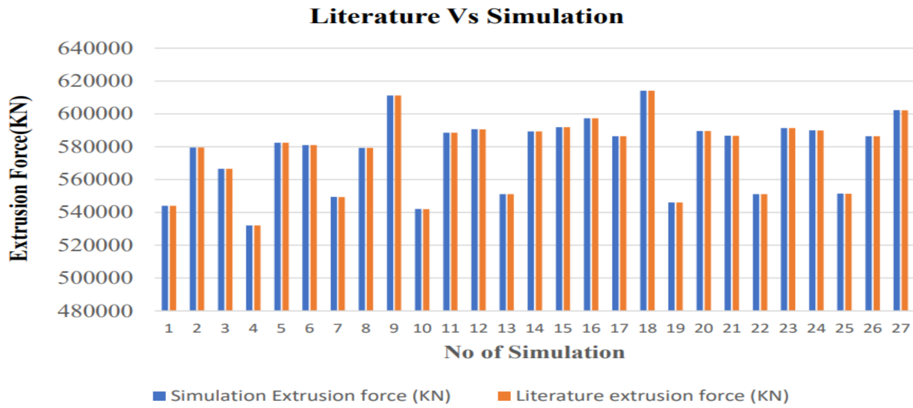


Figure 12. Literature vs simulation extrusion force

Figure 12 compares the simulated extrusion force with literature data, followed by Taguchi analysis to determine the optimal parameters. Table 2 highlights deviations in extrusion force values, indicating variability. Comprehensive analysis helps identify suitable extrusion conditions and minimize discrepancies.

Table 2. Comparison of simulation and literature extrusion force results of 20MnCr5 steel

Serial No	Logarithmic Strain	Die angle	Coefficient of friction	Extrusion Velocity (mm/sec)	Simulation Extrusion force (KN)	Literature extrusion force (KN)	Deviation of extrusion force
1	0.3080	20	0.08	1	544000	543970	30%
2	0.3080	30	0.1	1.5	579541	579523	18%
3	0.3080	40	0.12	2	566520	566499	21%
4	0.6040	20	0.08	1	532099	532040	59%
5	0.6040	30	0.1	1.5	582427	582401	26%
6	0.6040	40	0.12	2	581020	580922	98%
7	0.9040	20	0.08	1	549370	549342	28%
8	0.9040	30	0.1	1.5	579304	579285	19%
9	0.9040	40	0.12	2	611159	611132	27%
10	0.3080	20	0.12	1	542067	541988	79%
11	0.3080	30	0.1	1.5	588558	588519	39%
12	0.3080	40	0.08	2	590642	590563	79%
13	0.6040	20	0.12	1	551123	551049	74%
14	0.6040	30	0.1	1.5	589347	589320	27%
15	0.6040	40	0.08	2	591944	591923	21%
16	0.9040	20	0.12	1	597364	597333	31%
17	0.9040	30	0.1	1.5	586415	586391	24%
18	0.9040	40	0.08	2	614151	614131	20%

19	0.3080	20	0.1	1	546010	545979	31%
20	0.3080	30	0.08	1.5	589541	589521	20%
21	0.3080	40	0.12	2	586701	586560	141%
22	0.6040	20	0.1	1	551065	551048	17%
23	0.6040	30	0.08	1.5	591362	591339	23%
24	0.6040	40	0.12	2	590013	589925	88%
25	0.9040	20	0.01	1	551397	551343	54%
26	0.9040	30	0.08	1.5	586432	586392	40%
27	0.9040	40	0.12	2	602225	602133	92%

4.2 Taguchi Analysis

The Taguchi method is an efficient test programming approach that reduces the number of experiments needed to identify optimal process parameters. Using orthogonal arrays, this method evaluates factors that significantly impact the outcome and determines optimal settings based on the signal-to-noise (S/N) ratio. The S/N ratio helps minimize variability due to noise, enhancing product quality. In this study, Table 3 presents the Response Table for Means, while Table 4 shows the Signal-to-Noise Ratios, using the "Smaller is Better" criterion. The main effect plots for data means and S/N ratios (Figures 13 and 14) reveal that the coefficient of friction, die angle, extrusion velocity, and logarithmic strain significantly impact extrusion force, with variations of 14019 KN, 16026 KN, 7063 KN, and 5911 KN, respectively.

Table 3. Response Table for means

Level	Coefficient of friction	Die angle	Extrusion velocity	Logarithmic Strain
1	569493	570398	580048	573614
2	583512	573378	572985	579525
3	577194	586424	577167	577060
Delta	14019	16026	7063	5911
Rank	2	1	3	4

Table 4. Response Table for Signal-to-Noise ratios (Smaller is better)

Level	Coefficient of friction	Die angle	Extrusion velocity	Logarithmic Strain
1	-115.1	-115.1	-115.3	-115.2
2	-115.3	-115.2	-115.2	-115.3
3	-115.2	-115.4	-115.2	-115.2
Delta	0.2	0.2	0.1	0.1
Rank	2	1	3	4

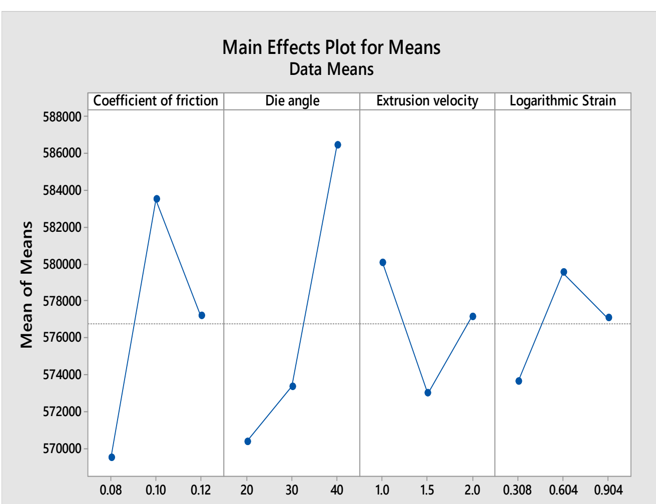


Figure 13. Main effect plot for data

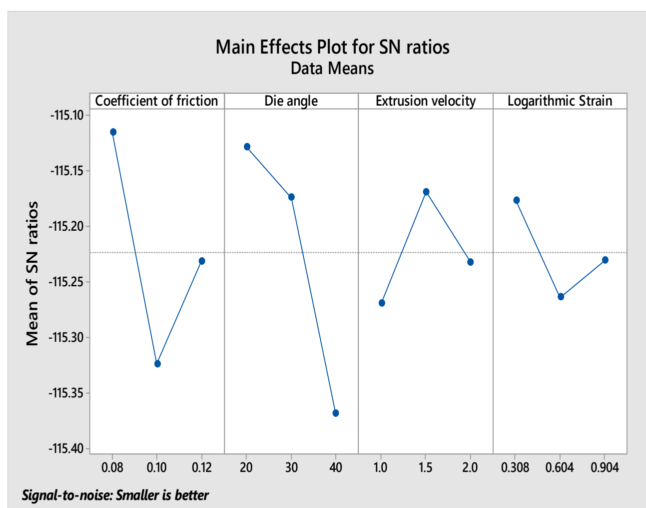


Figure 14. Main effect plot for S/N ratios

4.3 Regression Analysis

Regression analysis uses various statistical methods to estimate the relationship between a variable and one or more other variables. It can be used to model future relationships between variables and quantify their relationship. Table 5 shows the optimum values of input parameters to obtain the minimum extrusion force for the extrusion process. The dependent variable is the extrusion force, while the independent variables are the coefficient of friction, dead angle, logarithmic strain, and extrusion speed. The estimate based on factorial linear regression analysis is shown below.
Extrusion Force = 576733-7240 Coefficient of friction 0.08+6779 Coefficient of friction 0.1+461 Coefficient of friction 0.12-6335 Die angle 20-3355 Die angle 30+9691 Die angle 40+3315 Extrusion velocity 1.0-3748 Extrusion velocity 1.5+433 Extrusion velocity 2.0-3119 Logarithmic Strain 0.308+2792 Logarithmic Strain 0.604+327 Logarithmic Strain 0.904.

Table 5. Optimum value from regression analysis

Coefficient of friction	Die angle	Ram velocity (mm/sec)	Logarithmic Strain	Extrusion Force (KN)
0.08	20	1.5	0.308	556291

4.4 ANOVA Analysis

This study examines the influence of four extrusion parameters: coefficient of friction, die angle, logarithmic strain, and ram velocity, on the extrusion force in 20MnCr5 alloyed steel. Understanding their effects is crucial to identifying which parameter significantly impacts the extrusion force. According to the ANOVA results summarized in Table 6, the P-values indicate the statistical significance of each factor. The die angle, with a contribution of 43.45%, showed the highest impact on extrusion force, followed by the coefficient of friction at 29.48%. In contrast, logarithmic strain and ram velocity had a smaller influence, contributing 5.28% and 7.55%, respectively. The F-values, all differing significantly from unity, support the rejection of the null hypothesis, confirming that each of these factors significantly affects the extrusion force. Figure 15 visually illustrates the impact of these parameters, emphasizing the critical role of die angle in the extrusion process of 20MnCr5 steel.

Table 6. Results of ANOVA for extrusion force

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Coefficient of friction	2	4436309465	2218154730	12.35	0.023	29.48%
Die angle	2	6538958605	2218154730	103.12	0.001	43.45%
Extrusion velocity	2	1135003360	567501680	8.37	0.045	7.54%
Logarithmic Strain	2	793356125	396678060	6.39	0.051	5.27%
Error	18	2145923158	119217953.2			14.26%
Total	26	15049550713				100.00%

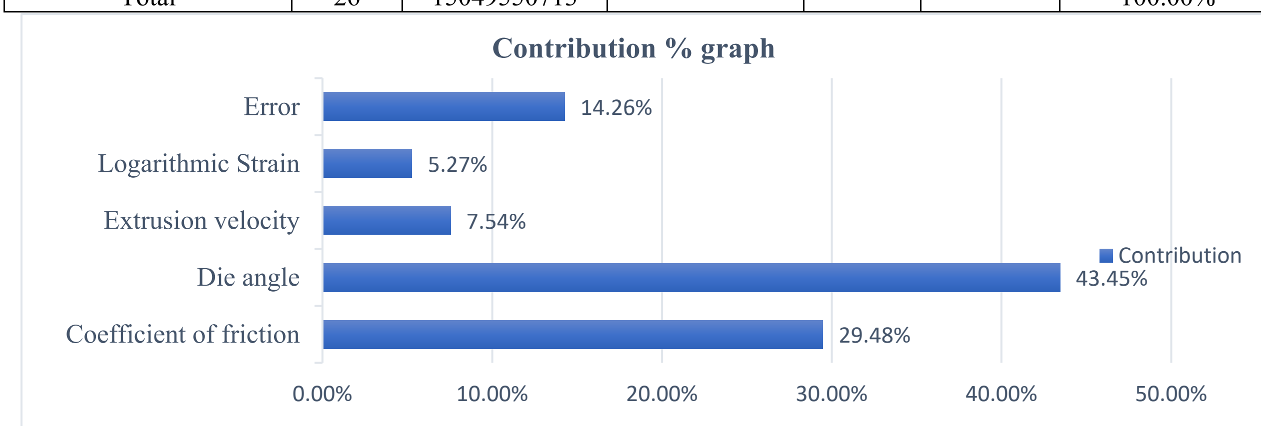


Figure 15. Contribution graph of extrusion parameters for extrusion force

4.5 Effects of Extrusion Speed or Ram Velocity on Temperature

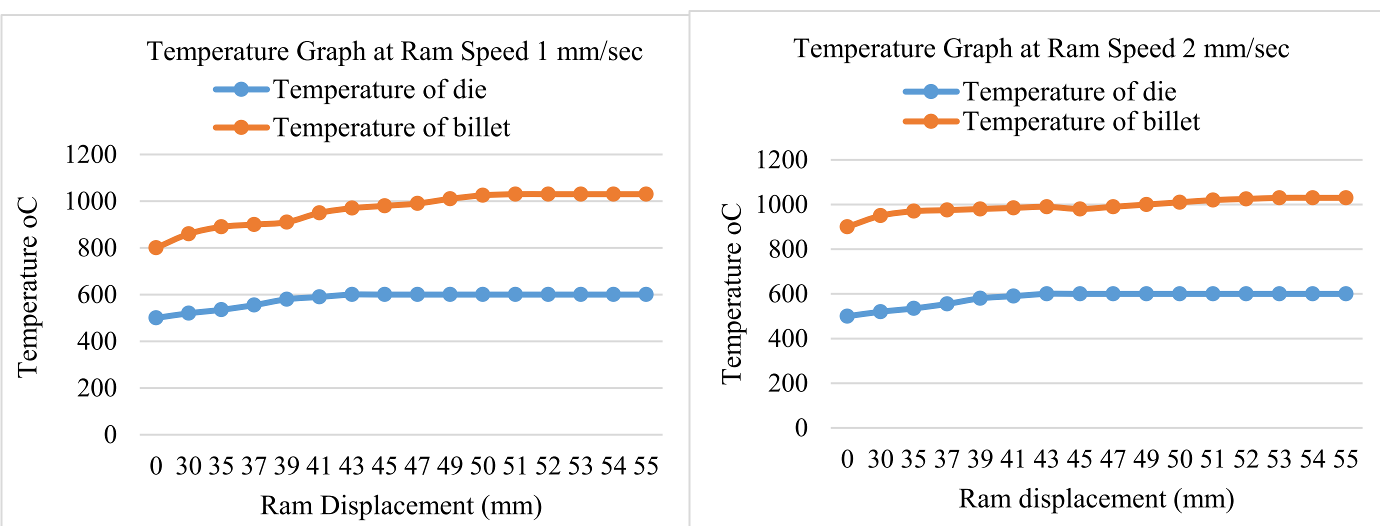
The maximum billet temperature typically does not align with the peak temperature of the die, particularly at higher ram speeds. This temperature discrepancy is evident when the ram speed increases, as shown in Figure 16, which illustrates temperature fluctuations under various extrusion conditions. During extrusion, stable temperature measurement is achieved once the ram displacement reaches 0 mm. The temperature variation significantly affects material flow, as indicated by Table 7, which compares the maximum temperatures of the billet and die at ram speeds of 1 mm/s and 2 mm/s. Computer simulations help predict temperature changes more accurately than direct measurements, which can be influenced by device precision. For a ram speed of 1 mm/s, Figure 16(a) shows the temperature progression of the billet and die, with initial temperature sensitivity more dependent on geometry than speed.

Table 7 (a). Evaluation of the maximum temperatures of the extruded and die during the extrusion at a ram speed of 1 mm/s

Displacement (mm)	Temperature of die °C	Temperature of billet °C
0	500	800
30	520	860
35	535	890
37	555	900
39	580	910
41	590	950
43	600	970
45	600	980
47	600	990
49	600	1010
50	600	1025
51	600	1030
52	600	1030
53	600	1030
54	600	1030
55	600	1030

Table 7 (b). Evaluation of the maximum temperatures of the extruded and die during the extrusion at a ram speed of 2 mm/s

Displacement (mm)	Temperature of die °C	Temperature of billet °C
0	500	900
30	520	950
35	535	970
37	555	975
39	580	980
41	590	985
43	600	990
45	600	980
47	600	990
49	600	1000
50	600	1010
51	600	1020
52	600	1025
53	600	1030
54	600	1030
55	600	1030



(a) (b)

Figure 16. Evaluation of the maximum temperatures of the extruded and die during the extrusion; (a) at ram speed of 1 mm/s; (b) at ram speed of 2 mm/s

At 2 mm/s, Figure 16(b) illustrates a further rise in billet temperature, surpssing its initial state, indicating the influence of ram speed on heat generation and loss during extrusion. The analysis of extrusion speed's effect on temperature revealed a maximum die temperature of 600°C and billet temperature of 1030°C at ram speeds between 1-2 mm/s.

4.6 Effects of Temperature on Stress

The interplay between temperature and stress is crucial in the extrusion process, significantly influencing material behavior. As the temperature increases, the material stress generally decreases, enhancing its flow through the die and reducing the overall extrusion force. For steels like 20MnCr5, elevated temperatures facilitate smoother flow and lower the required extrusion force, as detailed in Table 8. The data shows that the maximum stress of 1000 MPa occurs at a low temperature of 20°C with 0.7% strain, while a minimum stress of 90 MPa is observed at 1050°C with 0% strain. However, excessively high temperatures can lead to issues such as oxidation or material degradation, whereas lower temperatures increase viscosity, making extrusion more challenging and potentially causing defects like brittleness or cracking. Figure 17 illustrates the flow stress dependency on temperature, highlighting how variations in temperature impact the stress-strain behavior during extrusion.

Table 8. Effects of temperature on stress and strain

SL. No.	Temperature (◦C)	Strain (%)	Stress (MPa)	SL. No.	Temperature (◦C)	Strain (%)	Stress (MPa)
1	20	0	400	19	600	0.6	480
2	20	0.2	820	20	600	0.7	450
3	20	0.4	910	21	750	0	200
4	20	0.6	990	22	750	0.2	290
5	20	0.7	1000	23	750	0.4	285
6	300	0	300	24	750	0.6	280
7	300	0.2	620	25	750	0.7	265
8	300	0.4	720	26	900	0	100
9	300	0.6	780	27	900	0.2	200
10	300	0.7	800	28	900	0.4	210
11	450	0	320	29	900	0.6	215
12	450	0.2	685	30	900	0.7	225
13	450	0.4	700	31	1050	0	90
14	450	0.6	675	32	1050	0.2	120
15	450	0.7	660	33	1050	0.4	140
16	600	0	300	34	1050	0.6	145
17	600	0.2	510	35	1050	0.7	145
18	600	0.4	500				

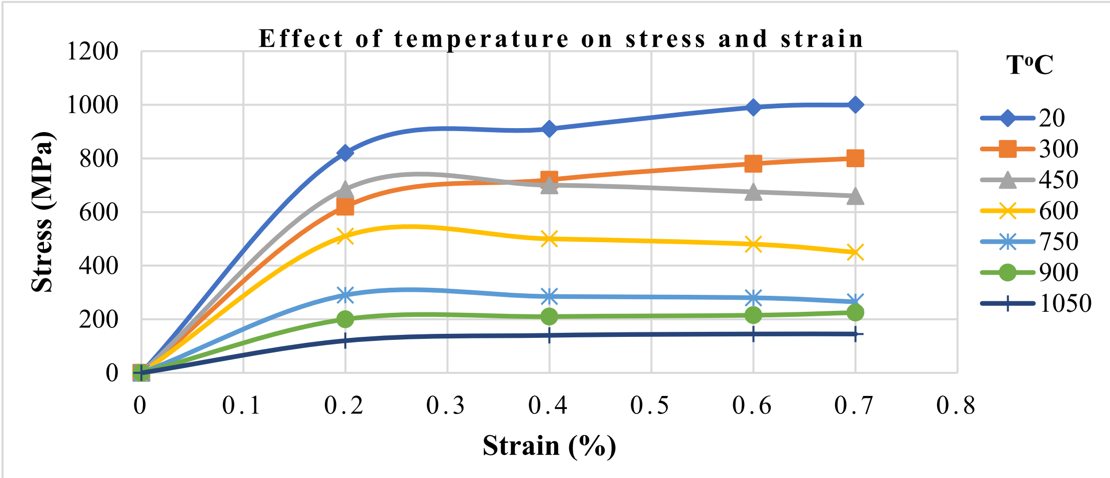


Figure 17. Effects of temperature on stress and strain

5. Conclusion

This study effectively utilized finite element analysis (FEA) via DEFORM 3D software, combined with statistical tools like Taguchi and ANOVA from MINITAB, to optimize the extrusion process parameters for 20MnCr5 alloy steel. The simulations offered valuable insights into material flow, stress distribution, and thermal behavior during extrusion, revealing how parameters such as die geometry, ram speed, and friction coefficient impact extrusion performance. Optimal conditions were identified, including a friction coefficient of 0.08, a die angle of 20°, and a ram speed of 1.5 mm/s, resulting in a minimized extrusion force of 556,291 KN. Analysis of the extrusion speed effect highlighted maximum temperatures of 600°C for the die and 1030°C for the billet at ram speeds of 1-2 mm/s. The temperature-stress relationship analysis indicated peak stress at 1000 MPa at 20°C and minimal stress at 90 MPa at 1050°C. The integration of DEFORM 3D with MINITAB proved to be an efficient approach for optimizing process parameters, enhancing the quality and efficiency of extruded products. Future research could explore varying die geometries and temperature settings to further reduce extrusion forces. To further enhance the extrusion process, future research should explore varying die geometries, advanced cooling strategies, and the effects of different material compositions. Incorporating real-time temperature and stress monitoring in experiments could also help in refining simulation models and improving predictive accuracy.

References

Akhgar, J., Mirjalili, A., Serajzadeh, S. J. P. o. t. I. o. M. E., Part L: Journal of Materials: Design, & Applications. (2011). An Investigation into the Deformation Behaviour of AA6061—5% SiCp Composite During and after Hot Extrusion Process. *225*(1), 22-31.

Altan, T., & Kobayashi, S. (1968). A numerical method for estimating the temperature distributions in extrusion through conical dies.

Chaudhari, G., Andhale, S., Patil, N. J. I. J. o. E. T., & Engineering, A. (2012). Experimental evaluation of effect of die angle on hardness and surface finish of cold forward extrusion of aluminum. *2*(7), 334-338.

Ebrahimi, M., Gholipour, H., Djavanroodi, F. J. M. S., & A, E. (2016). A study on the capability of equal channel forward extrusion process. *650*, 1-7.

Hojda, S., Sturm, K. J., Terhorst, M., Klocke, F., & Hirt, G. J. P. e. (2017). Damage dependent material properties in a Finite Element Simulation of a hybrid forward extrusion process. *207*, 437-441.

Jurković, Z., Brezočnik, M., Grizelj, B., & Mandić, V. J. T. v. (2009). Optimization of extrusion process by genetic algorithms and conventional techniques. *16*(4), 27-33.

Jurkovic, Z., Jurkovic, M., Buljan, S. J. J. o. A. i. m., & engineering, m. (2006). Optimization of extrusion force prediction model using different techniques. *17*(1-2), 353-356.

Karayel, D. J. K. e. m. (2008). Simulation of direct extrusion process and optimal design of technological parameters using FEM and artificial neural network. *367*, 185-192.

Khosravifard, A., Ebrahimi, R. J. M., & Design. (2010). Investigation of parameters affecting interface strength in Al/Cu clad bimetal rod extrusion process. *31*(1), 493-499.

KK, P. J. I. j. o. e., & sciences, m. (2007). Optimization of Die Angle and ram Velocity for Rod Extrusion Using Dynamic Material Modeling and Generic Algorithm. *14*, 399-402.

Noorani-Azad, M., Bakhshi-Jooybari, M., Hosseinipour, S., & Gorji, A. J. J. o. m. p. t. (2005). Experimental and numerical study of optimal die profile in cold forward rod extrusion of aluminum. *164*, 1572-1577.

Parvizian, F., Schneidt, A., Svendsen, B., & Mahnken, R. J. G. M. (2010). Thermo-mechanically coupled modeling and simulation of hot metal-forming processes using adaptive remeshing method. *33*(1), 95-115.

Pourbahari, B., Mirzadeh, H., Emamy, M., & Roumina, R. J. A. E. M. (2018). Enhanced ductility of a fine-grained Mg–Gd–Al–Zn magnesium alloy by hot extrusion. *20*(8), 1701171.

Ramesh, S., & Karunamoorthy, L. (2013). *Turning investigations on machining of Ti64 alloy with different cutting tool inserts.* Paper presented at the Materials Science Forum.

Research, C. Metal forming : fundamentals and applications. Retrieved from https://cir.nii.ac.jp/crid/1130282272570200960

Sahu, R. K., Das, R., Dash, B., & Routara, B. J. M. T. P. (2018). Finite element analysis and experimental study on forward, backward and forward-backward multi-hole extrusion process. *5*(2), 5229-5234.

Schikorra, M., Donati, L., Tomesani, L., & Tekkaya, A. J. J. o. M. P. T. (2008). Microstructure analysis of aluminum extrusion: Prediction of microstructure on AA6060 alloy. *201*(1-3), 156-162.

Silva, M. B., Carneiro, L. M., Silva, J. P. A., dos Santos Oliveira, I., Izário Filho, H. J., & de Oliveira Almeida, C. R. J. A. J. o. A. C. (2014). An application of the Taguchi method (robust design) to environmental engineering: Evaluating advanced oxidative processes in polyester-resin wastewater treatment. *2014*.

Subramanian, C., Palaniradja, K. J. I. J. o. A. T., & Exploration, E. (2018). Experimental investigation of mechanical properties on Al 7075 using electroless Ni-P/Ni-B duplex coating with nano SiC. *5*(39), 30-36.

Tahmasbi, K., & Mahmoodi, M. J. J. o. M. P. (2018). Evaluation of microstructure and mechanical properties of aluminum AA7022 produced by friction stir extrusion. *32*, 151-159.

Valberg, H. S. (2010). *Applied Metal Forming: Including FEM Analysis*: Cambridge University Press.

Yu, J., & Zhao, G. J. M. C. (2018). Interfacial structure and bonding mechanism of weld seams during porthole die extrusion of aluminum alloy profiles. *138*, 56-66.

Zhou, J., Li, L.-x., & Duszczyk, J. J. J. o. M. P. T. (2003). 3D FEM simulation of the whole cycle of aluminium extrusion throughout the transient state and the steady state using the updated Lagrangian approach. *134*(3), 383-397.

Zhou, W., Shi, Z., Lin, J. J. I. J. o. L. M., & Manufacture. (2018). Upper bound analysis of differential velocity sideways extrusion process for curved profiles using a fan-shaped flow line model. *1*(1), 21-32.

Biographies

Rotan Kumar Saha is a dynamic and energetic researcher who completed his M.Sc. in Mechanical Engineering at Dhaka University of Engineering & Technology (DUET), Gazipur. He holds an undergraduate degree from the Department of Industrial and Production Engineering at DUET. His research interests include a broad range of advanced manufacturing topics such as additive manufacturing, 3D printing, lean manufacturing, Lean Six Sigma, Total Quality Management (TQM), and optimization techniques.

Md. Touhiduzzaman is an enthusiastic researcher. He is currently studying M.sc Engineering department of Mechanical Engineering at Dhaka University of Engineering & Technology, Gazipur. He is a graduate student of the Department of Industrial and Production Engineering at DUET. His areas of interest in research include Manufacturing, Bio-Materials, Advanced Materials, Quality management etc.

Md. Mamun is a motivated researcher and a graduate student in the Department of Mechanical Engineering at Dhaka University of Engineering & Technology, Gazipur. His research interests span a wide range of innovative and sustainable fields, including sustainable energy, renewable energy, and green energy.

Md. Tareque Hasan is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include Manufacturing, Modeling & simulations, Data Analytics and Machine Learning, Optimization, Operation research etc. He is very much interested to be a part of IEOM.

Safayet Hossain is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include Optimization, Advance Manufacturing, Modeling & simulations, 3D printing. He is very much interested to be a part of IEOM.

Md. Rafiqul Ialam is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include Manufacturing, Optimization, 3D printing and Additive manufacturing.

Md. Nazmul Hasan is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include Manufacturing, Green Supply Chain, Optimization, 3D printing and additive manufacturing.

Tuhin Hosen is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include Manufacturing, Modeling & simulations, Optimization, 3D printing and Additive manufacturing. He is very much interested to be a part of IEOM.

Md Rahat Bhuyan is a student of the Department of Industrial & Production Engineering at Dhaka University of Engineering and Technology, Gazipur. His research interests include manufacturing, Supply Chain, Modeling & simulations, Optimization, 3D printing and Additive manufacturing. He is very much interested to be a part of IEOM.