



Detection Of Extrusion Defects : An AI Perspective & Analysis and Optimization in Pipe Extrusion

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ABSTRACT

Plastic pipe extrusion is a very critical manufacturing process for infrastructure and irrigation applications, yet it continues to suffer from recurring quality defects such as uneven wall thickness, variation in diameter, off-center issues, rough surface finish and cracks. These defects, primarily arising from improper control of key process parameters (take-off speed, barrel/die zone temperatures, vacuum pressure, and auxiliary speeds), improper material handling, moisture absorption, surging, poor mixing, overheating, melt fracture, trapped air, and contamination, reduced scrap rates, productivity. Integrating these findings, this work proposes that modern AI-based approaches— including machine learning models for real-time defect classification from inline sensor data (temperature, pressure, screw speed, puller speed, vacuum, melt flow proxies) predictive quality modeling, parameter optimization via reinforcement learning can substantially advance beyond classical Taguchi DOE. Such AI-driven systems reduced dependence on offline experimentation, and further minimization of defects and quality costs in high-volume plastic pipe extrusion. Keywords:- Plastic pipe extrusion, Extrusion defects, Taguchi method, process optimization, AI-based defect detection, Predictive quality control

I. INTRODUCTION

Extrusion is any process in which a material is force through a shaped orifice, with the material solidifying to produce a continuous length of constant cross section. Squeezing toothpaste from a tube is a familiar example [1]. In extrusion of plastic, thermoplastic were softened by Providing heat prior to extrusion Process and, after the shape to be held as per required; the thermoplastics must be quickly quenched and, usually, supported while cooling. Some Extra large extruders in polymer plants are fed hot melts, so their main duty is generating enough pressure to force out the melt through spider die. In most extrusion operations, however, the plastics arrive as powders grannuals or pellets at room temperature, and the extrusion process must heat & melt the plastic and homogenize it before it enters the die. Therefore, heating and melting the feedstock, converting it from a cold solid to a hot viscous liquid, accounts for about 93% of the energy required. The work done in pumping the melt through the die is only 5-10% of the total [2].

II. EXTRUESION PROCESS

Plastic extrusion is a bulk-volume manufacturing process in which raw thermoplastic is heat& melt and formed into a continuous proper requied profile. This process starts from by feeding plastic material (pellets, granules, flakes or powders vergine, resins and some addetives) from a hopper into the cylinder of the extruder. The material is gradually melted by the mechanical energy generated by turning screws and by heaters arranged along the barrel.[3] The molten polymer is then forced into a die, which shapes the polymer into a shape that hardens during cooling.[4]

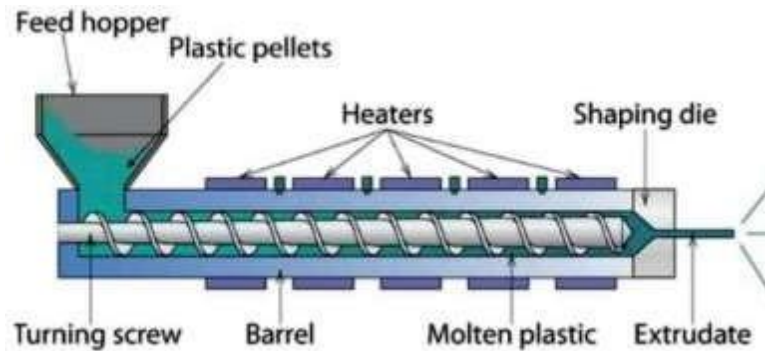


Fig. 1 Plastic Extrusion Process [5]

III. STEP-BY-STEP PROCESS

Here's how the extrusion process works in detail

1. Material Preparation:

Raw thermoplastic pellets (like polyethylene, PVC, or polypropylene) are loaded into the hopper. Additives such as colorants, stabilizers, or fillers may be mixed in.

2. Feeding and Melting:

Gravity feeds the pellets into the extruder's barrel. The rotating screw (driven by a motor) pushes the material forward. The barrel is divided into zones:

Feed Zone: Solids are compressed and preheated.

Compression Zone: Friction and external heaters (typically 150–250°C, depending on the polymer) melt the plastic into a viscous melt.

Metering Zone: The melt is homogenized and pumped under pressure (up to 5000 psi) toward the die.

3. Shaping Through the Die:

The molten plastic is forced through the die, which determines the shape. Die swell (where the extrudate expands slightly upon exiting due to elastic recovery) is accounted for in design.

4. Cooling and Sizing:

The hot extrudate enters a cooling stage immediately to set its shape. For example:- Pipes might pass through a vacuum calibration tank with water to maintain roundness. Sheets use chill rolls for flatness. Cooling must be controlled to avoid warping or internal stresses.

5. Downstream Processing:

The solidified product is cut (using saws or guillotines) or wound. Additional steps like printing, embossing, or coating can be integrated inline.

6. Quality Control:

Throughout, sensors monitor temperature, pressure, speed, and dimensions. Defects like uneven thickness or surface roughness can arise from inconsistent melt temperature or die issues.

The entire process is continuous, allowing for high production rates (e.g., thousands of meters per hour) with minimal waste if recycled.

IV. WHY OPTIMIZE PARAMETERS IN THE PLASTIC EXTRUSION PROCESS?

Optimization of parameters in plastic extrusion is crucial because the process involves a delicate balance of heat, pressure, flow, and cooling to produce high-quality, consistent products efficiently. Without optimization, issues like defects, waste, energy inefficiency, and inconsistent output can arise, leading to higher costs and lower productivity. Extrusion is a continuous, high-volume process, so even small improvements in parameters can yield significant gains in performance, quality, and sustainability. Below, I'll explain the need for optimization, key parameters involved, the impacts of poor settings, and the benefits.

Key Reasons for Optimization

1. Achieving Desired Product Quality:

Extruded products must meet specific standards for dimensions, strength, appearance, and functionality. Parameters directly influence the melt behavior, flow through the die, and final solidification. For instance, suboptimal settings can cause defects like sharkskin (rough surface), melt fracture (irregular flow), bubbles



(from moisture or overheating), or dimensional inaccuracies (e.g., uneven wall thickness in pipes).

2. Improving Process Efficiency and Throughput:

Extrusion lines run continuously, often 24/7, so optimizing for maximum output without compromising quality reduces downtime and increases production rates. Poorly tuned parameters can lead to frequent stops for adjustments or cleaning, wasting time and resources.

- It also minimizes energy consumption—extruders use significant heat and mechanical power, and fine-tuning can cut utility costs by 10-20% in some cases.

3. Reducing Material Waste and Costs:

Defects from non-optimized parameters result in scrap rates that can exceed 5-10%, especially during startup or material changes. Optimization helps achieve "first-pass yield," where products meet specs right away.

4. Ensuring Consistency and Repeatability:

Variations in ambient conditions (e.g., humidity, temperature) or raw material batches can affect the process. Optimization accounts for these, using sensors and controls to maintain stability across runs.

- This is especially important for regulated industries like automotive or food packaging, where batch-to-batch consistency is required for compliance (e.g., ISO standards or FDA regulations).

Key Parameters to Optimize and Their Impacts

Here are the main controllable variables, why they matter, and common optimization needs:

- **Temperature Profile (Barrel, Screw, Die):**

Typically 150-300°C, zoned along the extruder.

Need: Too low causes incomplete melting and high viscosity (leading to poor flow and defects); too high causes degradation, discoloration, or volatiles.

- **Screw Speed (RPM):**

Controls shear rate and output (e.g., 50-200 RPM).

Need: High speeds increase throughput but can overheat the melt or cause uneven mixing. Balancing with residence time prevents degradation while maximizing efficiency.

- **Pressure (Back Pressure, Die Pressure):**

Up to 5,000 psi.

Need: Maintains consistent flow; low pressure causes surging (pulsating output), high pressure risks equipment strain. Optimization via screen packs or die design ensures steady extrusion.

- **Feed Rate and Material Handling:**

Hopper feed consistency.

Need: Inconsistent feeding leads to starvation (air pockets) or flooding (overloading). Gravimetric feeders optimize for precise dosing, especially with blends or recycled materials.

- **Cooling Rate and Puller Speed:**

Cooling via water/air; puller at 1-50 m/min.

Need: Rapid cooling can cause internal stresses or warping; slow cooling allows sagging. Matching puller speed to extrusion rate controls dimensions (e.g., thickness via draw-down ratio).

V. METHODOLOGY FOR RESEARCH WORK

To optimize the process parameters in extrusion process following methodology followed.

- Select the plastic pipe manufacturing industry.
- Collection of data regarding the various defects in extrusion process.
- Finding out the parameter responsible for the defects and their causes.
- Apply the Taguchi's method by using AI tools
- Predict the process parameters', which is optimized. Compare the data with previous [6]

Steps to Implement AI in Taguchi for PVC Pipe Extrusion Optimization

Identify Key Parameters and Responses: Select controllable factors based on domain knowledge. For PVC extrusion, typical factors include:

- Barrel temperatures (e.g., zones 1-4: 160-200°C)
- Die temperature (180-210°C)
- Screw speed (20-50 RPM)
- Puller speed (1-5 m/min)



Design Experiments Using Taguchi:

Choose an orthogonal array (e.g., L9 for 4 factors at 3 levels). Assign levels to factors (e.g., low, medium, high). Run physical or simulated trials on the extruder, measuring responses. Calculate S/N ratios (e.g., "nominal-the-better" for thickness uniformity: $S/N = -10$)

Collect and Preprocess Data:

Gather data from Taguchi trials, including inputs and outputs. Augment with historical production data if available. Clean for outliers and normalize features for AI training.

Train AI/ML Models: Use the Taguchi dataset to train models:

ANNs: For nonlinear mapping (e.g., input layers for parameters, hidden layers for interactions, output for responses). Validate with cross-validation to avoid overfitting.

Optimize Using AI: Employ the trained model for:

Prediction: Simulate thousands of parameter combinations virtually to find optima (e.g., maximize S/N or minimize defects).

Response Surfaces

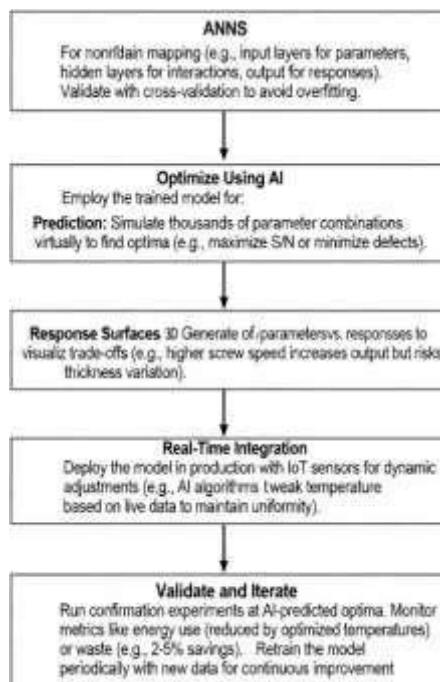
: Generate 3D plots of parameters vs. responses to visualize trade-offs (e.g., higher screw speed increases output but risks thickness variation).

Real-Time Integration:

Deploy the model in production with IoT sensors for dynamic adjustments (e.g., AI algorithms tweak temperature based on live data to maintain uniformity).

Validate and Iterate:

Run confirmation experiments at AI-predicted optima. Monitor metrics like energy use (reduced by optimized temperatures) or waste (e.g., 2-5% savings). Retrain the model periodically with new data for continuous improvement



Block Diagram :- Optimize Using AI: Employ the trained model for [1]

VI. PLANNING OF EXPERIMENT

Selection of industry

For research work Shivraj HY-Tech Drip Irrigation Company was selected this company is situated in MIDC Khamgaon, in Buldhana district of Maharashtra state in India.



Collection of data of Defect

Table. 1

Sr no.	Type of quality defects	Frequency of defect
1	Uneven Wall thickness (A)	3300
2	Centering problem(off-center) (B)	560
3	Diameter variation (C)	1900
4	Crack (D)	750
5	Discontinuity in drilling (E)	1198
6	Rough surface finishing (F)	86
Total		7794

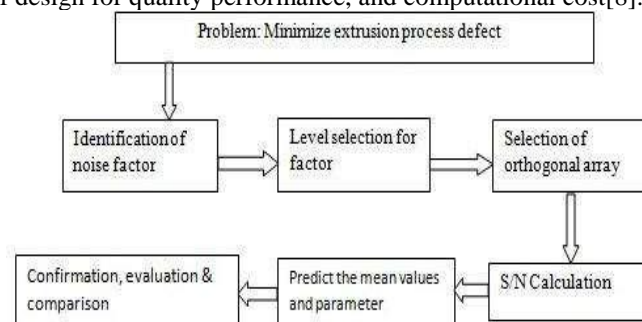
Data analysis-

From the above observation, it is confirmed that the uneven wall thickness is a very important parameter, which affects the Extrusion process and we are concentrating on the same.

VII. Apply Taguchi Method

a) Taguchi and Konashi developed Taguchi techniques

[7]; these techniques have been utilized mostly in engineering analysis to optimize the various performance characteristics within the combination of parameters. It introduced an integrated that is simple and efficient to find the optimum range of design for quality performance, and computational cost[8].



Blockdiagram 2: Taguchi's method

b) Notified influencing factors

- Take off Speed
- Temperatures
- Vacuum Pressure
- Relative speed of auxiliary

c) Factor Level Selection

Table. 2

HDPE Pipe ø 14smm/1.0					
Control factors (Temperature zones in °C , Take-off speed in m/min)	L	E	V	E	L
	Unit	1	2	3	
Take Off Speed	m/min	18	22	20	
Temperature 3	in °c	170	176	178	
Temperature 4	in °c	170	172	168	

d) S/N Calculation

Table. 3

Sr No	1	2	3	4	5	6	7	8	9
SNRA	51.1230	38.5830	35.0239	39.9647	65.1100	36.0365	37.4456	39.0219	35.2490
MEAN	13.9960	13.9958	14.0352	14.1011	14.0077	14.0682	14.1224	14.0896	14.1584

For this ø 14smm L9 orthogonal array is chosen and Taguchi's design is used. The mean response value and S/N



response value is shown in the table below.

Response Table Table. 4

Level	Take off Speed	Temp3	Temp4
1	14.07	14.08	14.06
2	14.03	14.04	14.06
3	14.14	14.10	14.09
Delta	0.10	0.07	0.04
Rank	1	2	3

Analysis of variance for means of F/C 14mm Table.5

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Take-Off Speed	2	0.019802	0.019769	0.009884	27.98	0.036
Temp 3	2	0.005120	0.005120	0.002565	7.26	0.122
Temp 4	2	0.002060	0.002060	0.010308	2.93	0.256
Residual Error	2	0.000780	0.000708	0.000355		
Total	8	0.027657	Total			

Response Table for S/N Ratio of F/C 14mm Table.6

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Take-Off Speed	2	143.74	144.77	72.38	0.45	0.695
Temp 3	2	225.51	224.55	112.35	0.69	0.595
Temp 4	2	95.24	94.25	47.13	0.30	0.778
Residual Error	2	328.10	328.99	164.50		
Total	8	92.47				

Analysis of variance for S/N ratio of F/C 14mm Table. 7

Level	Take off Speed	Temp1	Temp2
1	47.05	42.86	45.87
2	41.60	47.58	42.07
3	37.31	35.45	37.95
Delta	9.81	12.15	7.93
Rank	2	1	3

To select optimum setting of temperature values, the setting that results in a mean response value closing to the target value and that has a large or not significantly reduced S/N ratio is advised be considered.

From the analysis before and the main effects plot in the previous figures, factors and their respective levels selected for this product are:

Take off speed ----- 18 (level 1)

Temperature 3----- 170 (level 1)

Temperature 4 ----- 168 (level 1)

In addition, the predicted value of the response parameter at these temperature settings is Mean value -- 14.059mm

S/N ratio value-----51.84db

Standard deviation ----- 0.0821

Predict the mean value Predicted and Actual mean value of the product Table. 8

Product Type	Predicted Value		Target value (mm)	Actual mean value (mm)	Predicted mean value(mm)
	Mean	Standard			



	Diameter /width	wall thickness	Deviation			
F/C ø 14mm	14.060	Accepted	0.0822	14	13.935	14.060

Average quality loss before experiment for this product is

$$L = K (S^2 + (\mu - m)^2)$$

$$L = 64.577 * (0.122 + (13.935 - 14)^2)$$

$$L = 1.202 \text{ Rs/pc}$$

Average quality loss after experiment for this product is

$$L = K (S^2 + (\mu - m)^2)$$

$$L = 51.84 * ((0.0822 + (14.060 - 14)^2))$$

$$L = 0.535 \text{ Rs/pc}$$

Annual loss before and after experiment Table. 9

Type of Product	Loss due to deviation (Rs/Pc)		Annual Production (Kg)	Annual production in piece	Annual loss due to deviation (Rs)		Saving in Rs
	Before	After			Before	After	
F/C ø14	1.202Rs/pc	0.535Rs/pc	126000	1629000	1956429/-	871515	1084914/

% of Improvement

$$= \frac{(1.202 - 0.535)}{1.202} \times 100$$

$$= 55.49\%$$

$$\text{= \% of Improvement} = 55.49\%$$

VIII.CONCLUSION

Study being made in the company, the following conclusion were done, the improper setting of operational parameters, mixing raw material with wrong proportion, old machineries, poor testing and inspection of raw material are the reasons for the waste in the company. The study in the Extrusion process of a company shows that improper setting of operational parameters kept on a large share of the reason for scrap of the product and the study being conducted shows that setting of optimum operational parameters using Taguchi's method of design of experiment is a good technique in minimizing scrap rates and increases the Productivity. In addition, to apply the above setting parameters it was shown that the process improvement has been done about 55.49 %.

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