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Technical paper

Improving the Quality of High Density Polyethylene Pipes using Design of Experiments

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Abstract

The purpose of this work is to study quality related problems in polyethylene pipe products and to improve their quality. Design of Experiment methodology will be used in order to find the optimum settings of the production processes parameters and to reduce the defects. Based on data collected and after the analysis the significant factors are haul off speed, interaction between screw speed and temperature and interaction between screw speed and haul off speed. The results show that the optimum run was operating at high level off haul of speed and low level of screw speed and temperature, this run most of the samples that produced are match to the customers' specification.

Keywords: *Full Factorial Design; Polyethylene Pipes; Extrusion; Quality Improvement; Case Study*

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1. Introduction

Extrusion is one of the fundamental shaping processes of metal and ceramics as well as polymers. Extrusion is a compression process in which the material forced to flow through a die orifice to provide long and continuous products whose cross sectional shape is determined by the shape of the orifice. As a polymer shaping process, it is widely used for thermoplastics and elastomer to mass produce items such as tubing, pipes, hose structural shapes (such as window and door molding), sheet and film, continuous filaments, and coated electrical wire and cable. For these types of products, extrusion is curried out as a continuous process; the extruded product is subsequently cut into desired lengths.[2]

A number of defects can afflict extruded products. One of the worst is melt fracture, in which the stresses acting on the melt immediately before and during its flow throw the die are so high to cause failure. Manifested in the form of a highly irregular surface in the extruded product. melt fracture can be caused by a sharp reduction at the die entrance, causing turbulent flow that breaks up the melt. [5]

A more common defect in extrusion is sharkskin, in which the surface of the product becomes roughened upon existing the die. As the melt flows through the die opening, friction at the interface results in a velocity profile across the cross section. Tensile stresses develop at the surface as this material is stretched to keep up with the faster moving center core. These stresses cause minor rupture that roughen the surface. If the velocity gradient becomes extreme, permanent marks occur on the surface, giving it the appearance of a bamboo pole; the name bambooing for this more sever defect.[5]

Today, plastic materials used for pipes are classed under thermosetting or thermoplastic resins. Plastic highway drainage pipes belong almost entirely to the thermoplastic group (most commonly, high-density polyethylene (HDPE), PVC and ABS). They exhibit attributes of toughness, flexibility, chemical resistance and non-conducting electrical properties. Thermoplastic highway drainage pipes have been used for highway drainage since the early 1970s. Since then, growing out of applications for agricultural drainage, more HDPE drainage pipes have been installed than all other plastic pipes combined. They are being used for storm sewers, perforated under drains, storm drains, slope drains, cross drains and culverts.

Piping made from polyethylene is a cost effective solution for a broad range of piping problems in municipal, industrial, marine, mining, landfill, duct and agricultural applications. It has been tested and proven effective for above ground; surface, buried, slip lined, floating, and sub-surface marine applications.[6]

High-density polyethylene pipe (HDPE) can carry potable water, wastewater, slurries, chemicals, hazardous wastes, and compressed gases. In fact, polyethylene pipe has a long and distinguished history of service to the gas, oil, mining and other industries. It has the lowest repair frequency per mile of pipe per year compared with all other pressure pipe materials used for urban gas distribution.

Polyethylene is strong, extremely tough and very durable. Whether you're looking for long service, trouble-free installation, flexibility, resistance to chemicals or a myriad of other features, lightweight and a cost effective replacement for metal pipes, high-density polyethylene pipe will meet all daily life requirements.

1.1. Problem statement

In the extrusion process of Polyethylene Pipes one critical issue is the pipe thickness, pipes that are too thin will fail, and are considered of low quality. On the other hand, extra thick pipes are considered a waste of raw material and processing time that the customer is not going to pay for. The problem hence is selecting the exact process parameters to ensure optimal Polyethylene pipe thickness.

1.2. Objective

The main purpose of this work is to determine the most influential factors that are affecting the wall thickness in polyethylene pipe products. A second purpose of the work is to find the best possible configuration for the process. Then try to estimate the process capability after the proposed suggestion.

1.3. Importance

The work is considered a direct and simple method of proving Design of Experiments can be used to optimize the performance of production processes. It builds upon the results a number of works in this field. [8]

2. Design of Experiments

Design of Experiments (DOE) or an experimental design is a plan for assigning experimental units to treatment levels and the statistical analysis associated with the plan [9]. It is used to optimize the process. Well-designed experiments require less material, time and effort and provide more powerful insight than simple change-one-at-a-time experiment, DOE allows the experimenter to estimate the effects of a factor at different levels of other factors. This approach provides information about the interaction of various processing factors. Instead of changing one process setting at a time DOE can be used to develop a process that reduces the variability and improves capability [9]. The design of an experiment involves a number of inter-related activities. It starts with the definition of objectives of the study. Specifying the response variables to be measured, then development of the experimental design. Later on, running the experiment, collect and analyze data. Last steps include find significant factors and optimal settings. Finally, verification and application.

2.1. Factorial Designs

A full factorial design contains all possible combination of asset of factors. In full factorial designs, experiment runs are performed at every combination of the factor levels [4]. It is the most conservative design approach. There is little scope for ambiguity because all combinations of the factor settings are used. A factorial design is an arrangement in which all levels of each factor are combined with all levels of every other factor. There are many terms which connected to the factorial design, and it is defined as:

Factor: a variable or attribute that influences or is suspected of influencing the characteristic being investigated. For example: temperature, pressure, time etc.
Level: The values of a factor being examined in an experiment.
Response: The output hat needs to be improved

3. Methodology

As explained earlier, the most important problems are related to the pipe wall thickness. A local Palestinian company is chosen as a case study and a 16 mm diameter pipes were studied. The product wall thickness should be 1.9 mm with a tolerance of 0.1 mm. Parts with wall thickness greater than 2.2 mm or lesser than 1.8 mm are considered defective. Current historical information about the defective product percentage ranges in the region of 10% to 11%. The goal would be to decrease this rate.
This research paper has five phases:

1. The quality related problems in pipe wall thicknesses of the product is identified, studied in depth.
2. The process defects data is collected and measured in addition to inspecting the adequacy of the measurement system. Furthermore, the process capability study is performed to measure the process ability to meet the technical specification.
3. The quality problem is analyzed using design of experiments technique
4. The best process parameters are identified as a solution of the problem.
5. Some recommendations and suggestions to gain and control the expected gain are identified.

3.1. Problem on Hand

To understand better the problem, the process was studied, informal interviews with production line engineers and operators showed several issues that contributed to the problem. The production line manuals also indicated wall thickness could be caused by several parameters. After brainstorming three factors were identified as the study variables. Figure 1 shows the cause-and-effect diagram for different factors affecting the wall thickness of pipes.
The number of variables that could be studied is large. Some cannot be measured, some have low impact. The work will set the scope on the machine causes of the problem. Figure 2 shows the process parameters under study. Mainly three input parameters will be investigated. As currently the configuration is done by experience and a trial and error approach.

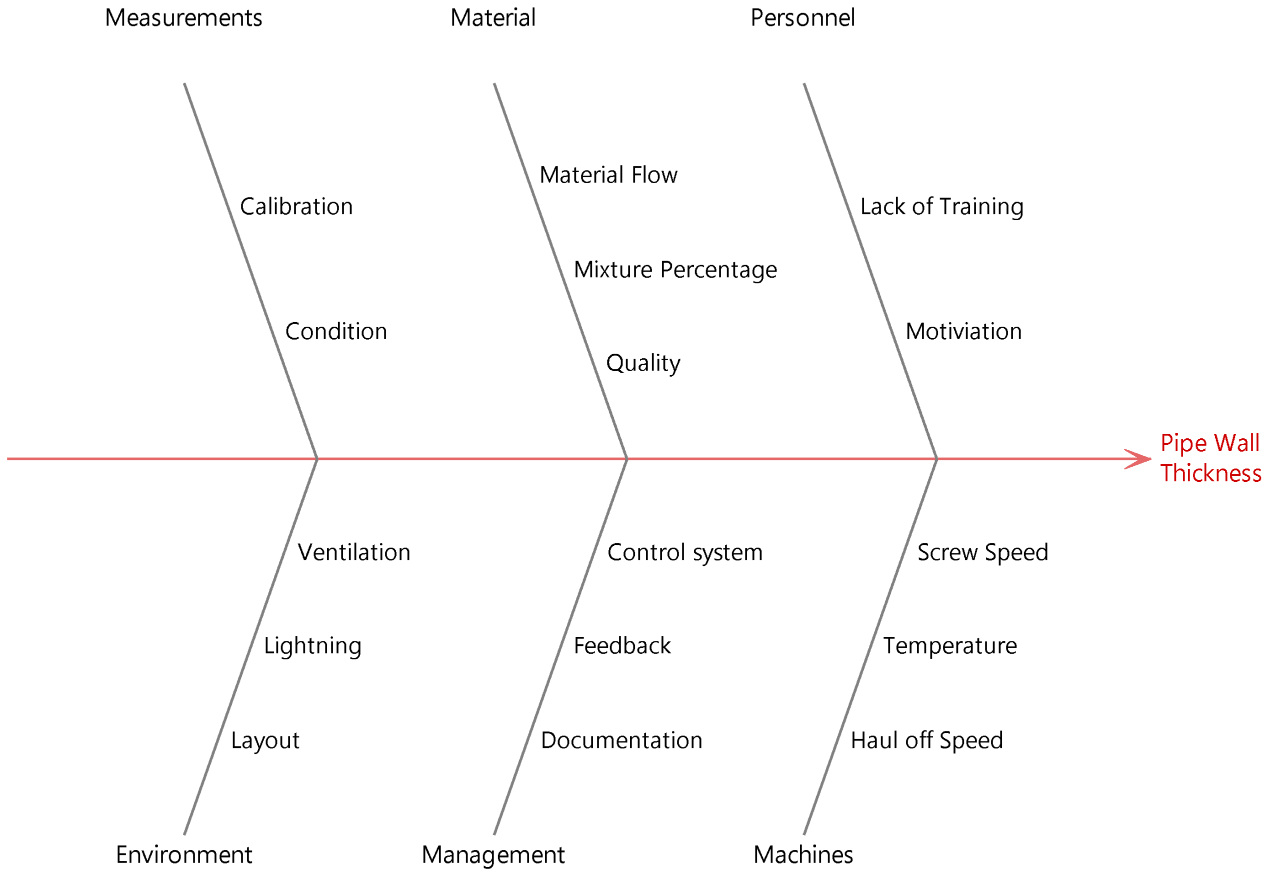

Figure 1: Cause and Effect Diagram for Issues Affecting the Wall Thickness

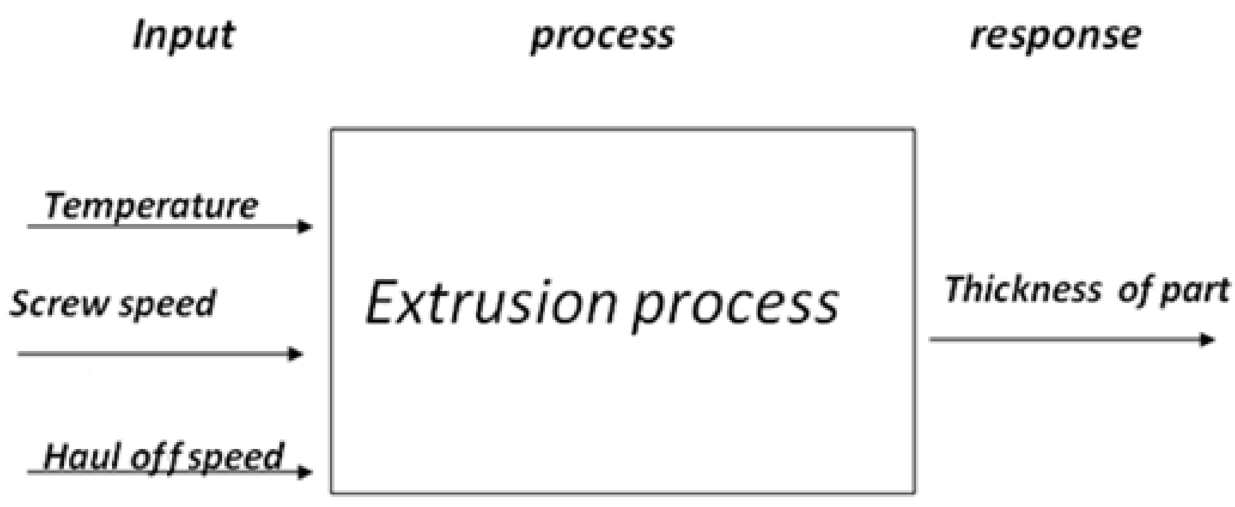

Figure 2: The Machine Parameters

Table 1: Suggested Process Parameters based on Machine Manual

Factor	Low Level	Upper Level
Head Temperature (^{o}C)	≤ 200	> 200
Haul off Speed (m/min)	< 7	≥ 7
Screw Speed (rpm)	≤ 155.9	≥ 161.9

Table 2: Full factorial experimental design from Minitab 17.0

Factorial Design	
Factors: 3	Base Design: 3, 8
Runs: 48	Replicates: 6
Blocks: 1	Center pts (total): 0

3.2. Data collection

The machine manuals suggest the following values for the process input parameters.

3.3. Applying Design of Experiments

A six replicate 2^3 Full Factorial Design was applied. The team used Minitab 17.0 to guide the implementation process in terms of run order and parameters. Table 2 shows the configuration of the experiment. A special template was used to fill the results obtained from the experiments.

4. Results

Before the results of the experimental design is shown. The team created a process capability analysis, shown in Figure 3. This gives the reader a better understanding on the problem on hand. It also shows that the process parameters needs to be adjusted.
Figure 3 also shows that keeping the current situation (randomly assigning the parameters) would produce products higher than and above the upper specification limit. The C_{pk} value of -0.12 revealed that the current process is not centered towards the mean and was not capable of producing the part well within the customer specification and that indicates that the mean of the process locates outside the specification limits.

After inputting the data into Minitab 17.0, a main factor effect plot was generated, depicted in Figure 4. It shows that the parameter ”Haul Off Speed” set on a lower speed, gives a thinner and closer to the desired thickness limits. The other two variables seemed to have no effect on the output.
One main added value of Design of Experiments approach is to study the second order interactions among factors. Figure 5 shows the level of interaction between the parameters of the process. It seems the level of interaction is high. It is easier to be read from the ANOVA table shown in Figure 6.
The ANOVA table presented in the output from Minitab 17.0 in Figure 6 shows that the model is significant, at $\alpha = 0.05$. However, the only main effect ”Haul-off speed” is significant at $\alpha = 0.05$. The other two factors are not significant, they seem to contribute in the second order/third order interactions. In fact all coefficients are positive, except the interaction between ”Temperature and Haul-off Speed” Which is on the verge of being significant.
To check the adequacy of the model, analysis of the residuals were done. Figure 7 from Minitab show some points being suspect outliers. The team decided to keep them as they do not invalidate the model. The team tested also for patterns in the residuals of the model or the fitted data with no concerns noted. Finally, the standardized residuals of the models were checked for normality, as shown in Figure 8. Again with no concerns to be reported. In conclusion the model can be used to study the thickness of the pipes. In fact, setting the parameters -1, -1 ,1 for “Temperature, Haul-off speed and Screw Speed” would give a mean thickness output of 1.97mm, the estimated standard deviation of the model is 0.036 mm. This indicated that about 79.76% of the produced pipes are expected to fall within specification. Which is considered a very low value, the process is way from being perfect.

5. Conclusion

This work presented an application of Design of Experiments (DOE) in optimizing the Extrusion process of High Density Polyethylene Pipes (HDPP). The analysis shows that even with the best parameters set the defect rate is over 20%. However this value is much better than before. Limitations of the this work is that it only focused on one product and mainly one defect type. More complexity would need a larger set of experiments, the study recommends that it would be worth it as the defective products percentage rate is high.

Acknowledgement

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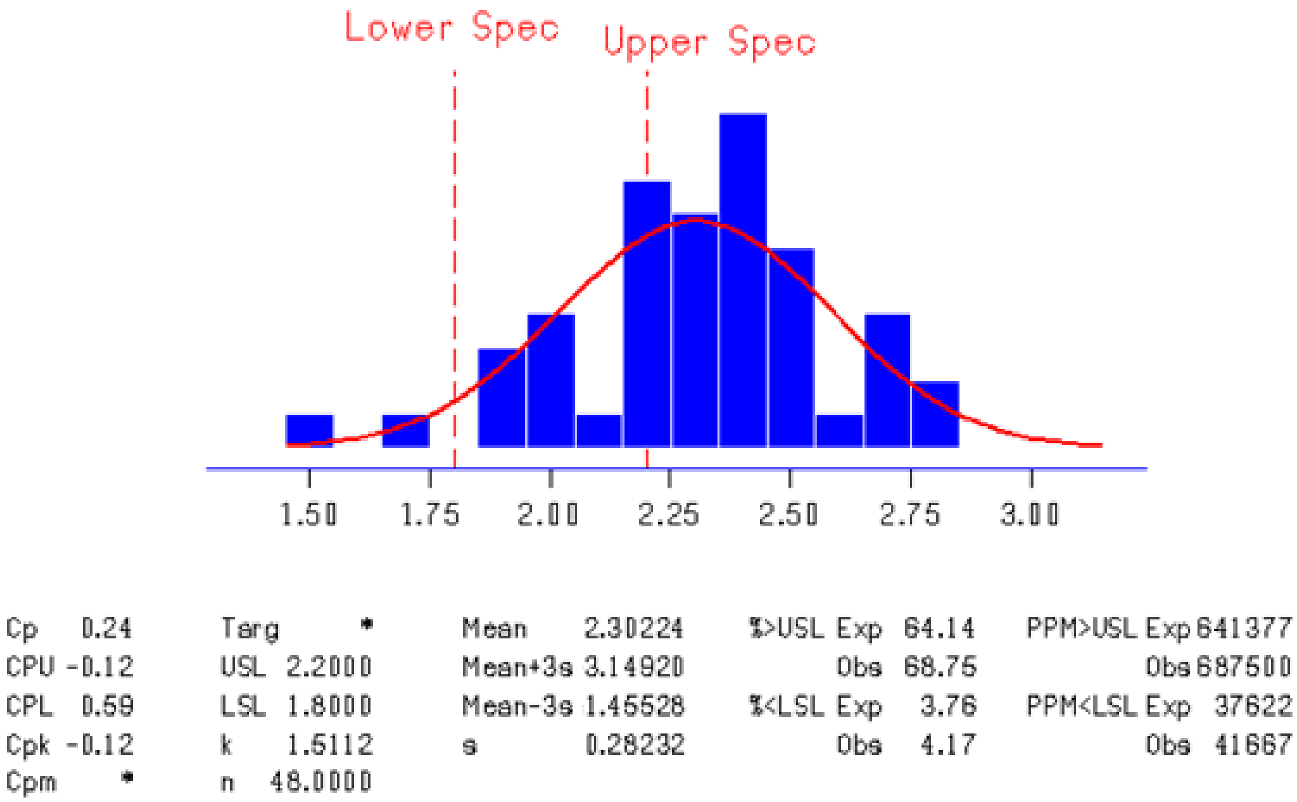

Figure 3: Process Capability Chart

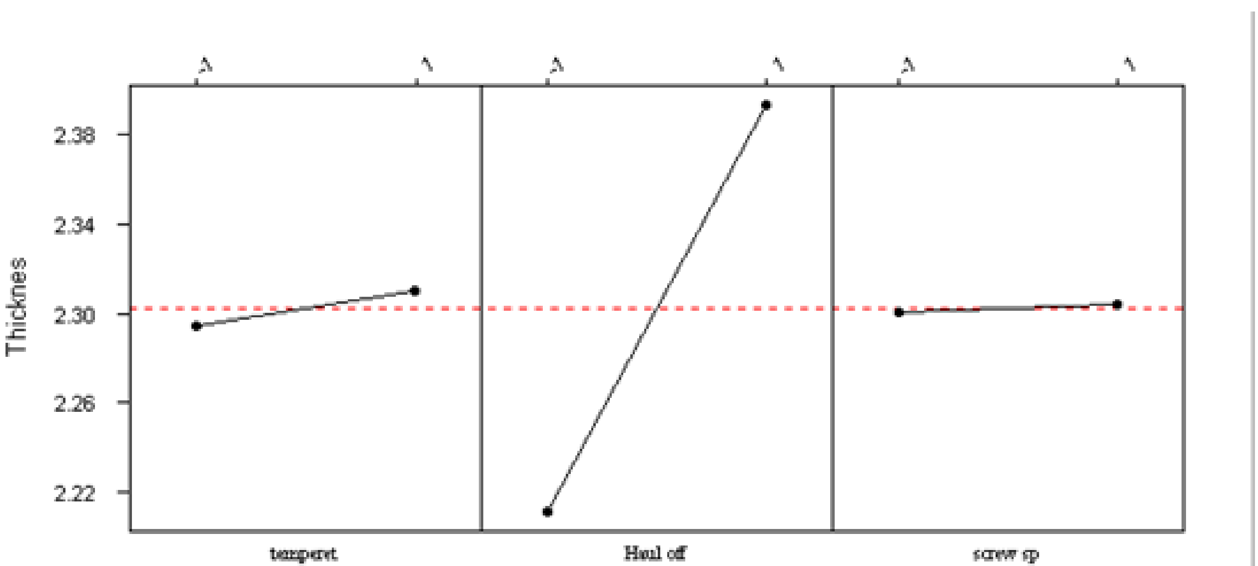

Figure 4: main effect plot

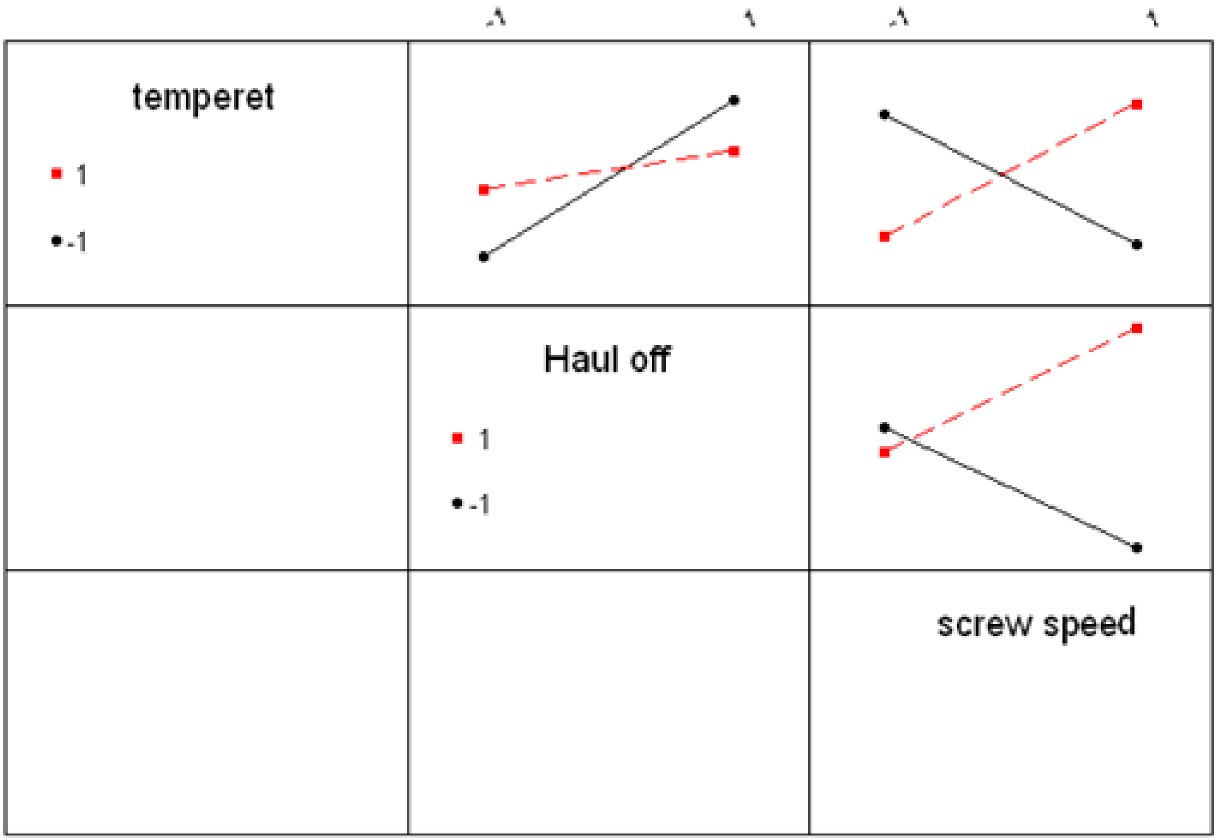

Figure 5: Interaction plot

Estimated Effects and Coefficients for Thicknes

Term	Effect	Coef	StDev Coef	T	P
Constant		2.30224	0.02742	83.96	0.000
Temperet	0.01594	0.00797	0.02742	0.29	0.773
Haul	0.18281	0.09141	0.02742	3.33	0.002
Screw	0.00323	0.00161	0.02742	0.06	0.953
Temperet*Haul	-0.11073	-0.05536	0.02742	-2.02	0.050
Temperet*Screw	0.24552	0.12276	0.02742	4.48	0.000
Haul*Screw	0.22781	0.11391	0.02742	4.15	0.000
Temperet*Haul*Screw	0.12177	0.06089	0.02742	2.22	0.032

Analysis of Variance for Thicknes

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.4042	0.4042	0.13474	3.73	0.019
2-Way Interactions	3	1.4933	1.4933	0.49776	13.79	0.000
3-Way Interactions	1	0.1779	0.1779	0.17794	4.93	0.032
Residual Error	40	1.4438	1.4438	0.03610		
Pure Error	40	1.4438	1.4438	0.03610		
Total	47	3.5192				

Figure 6: Full Factorial Results from Minitab 17.0

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Unusual Observations for Thicknes

Obs   Thicknes       Fit  StDev Fit   Residual   St Resid
  2    1.46250   1.97333    0.07756   -0.51083     -2.95R
  7    2.32750   1.97333    0.07756    0.35417      2.04R
 15    2.68000   2.32458    0.07756    0.35542      2.05R
 18    2.47000   1.97333    0.07756    0.49667      2.86R

R denotes an observation with a large standardized residual
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Figure 7: Outliers list from Minitab 17.0

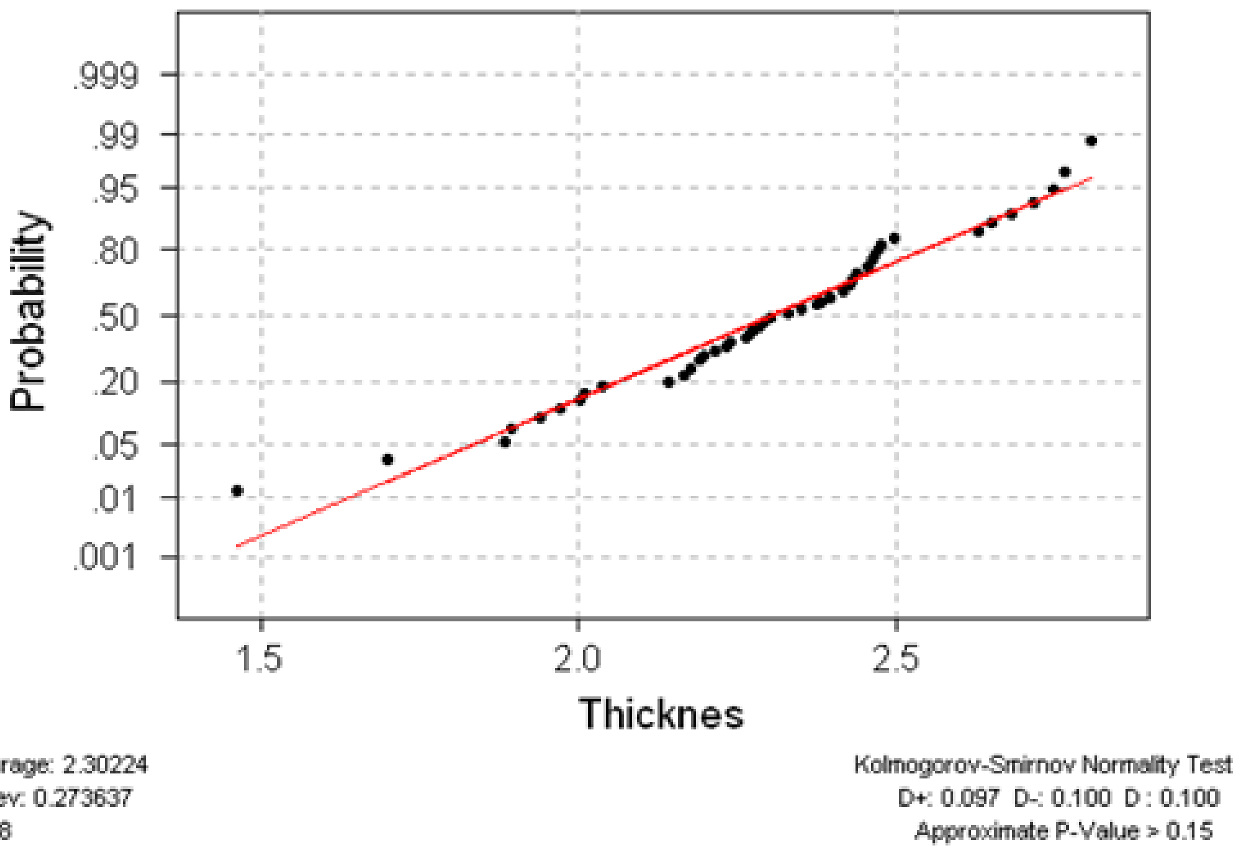

Figure 8: Full Factorial Results from Minitab 17.0

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