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RESEARCH PAPER

Improving Product Quality of Wire Drawing Process Using Design of Experiments

Mohamed S. Abdelwahed [a], Abdulaziz Alghamdi [a], Mohamed A. Eltaher [a, b, *]

[a] *Department of Mechanical Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia*
[b] *Department of Mechanical Design and Production, Faculty of Engineering, Zagazig University, Egypt*

Abstract

The wire drawing process is an essential technique in mechanical and industrial operations in lots of applications. Therefore, the current article aims to employ different methodologies (i.e., experimental, numerical) to investigate the optimum operating conditions and lubrication type on the surface and mechanical quality of these wires. By examining the effects of die angle, drawing speed, and lubricant type on wire drawing outcomes, the research not only provides valuable insights into process optimization but also contributes to reducing defects and enhancing wire properties. Results demonstrate significant variations in tensile strength based on these parameters, highlighting the need for precise control over process variables to achieve desired outcomes consistently. Moreover, statistical analyses reveal substantial relationships between process variables and tensile strength, offering a deeper understanding of the underlying mechanisms driving wire drawing performance. Overall, this research not only advances the understanding of wire drawing processes but also offers practical insights for improving wire manufacturing techniques, ultimately bolstering product quality, reducing costs, and increasing competitiveness in the global market.

Keywords: Wire drawing; Tensile Strength; Speed of drawing; Design of experiments.

1. Introduction

The term wire drawing refers to a variety of mechanical devices used in industrial settings. It is a method of metalworking that reduces the cross section of wire by pulling it through a series of dies. This forging technique is employed. Forging is the process of permanently altering a metal's form. At hot, warm, or cold temperatures, metal can be forged. Given that metals have varying properties depending on their temperature, it is possible that the characteristics of the metal will change as the temperature increases. When wire is drawn at room temperature, the development of dislocation density, reduction of interlamellar spacing and the refinement of grains size which leads to a strong hardening of the wires [1]. That explains the increase of the tensile strength from *1242 MPa* to *2618 MPa* with higher deformation. Also, the cementite lamellae are rotated toward the drawing axis and the thickness of lamellae further decreases when strain level increases, this phenomenon leads to a somewhat fibrous structure [2].

* Corresponding author M.A. Eltaher. Tel.: +966565518613
E-mail address: meltaher@kau.edu.sa, mohaeltaher@gmail.com

The origins of wire drawing can be traced back to ancient civilizations, where rudimentary forms of metalworking techniques were employed for crafting tools, ornaments, and weaponry. Early civilizations such as the Egyptians, Greeks, and Romans utilized basic wire drawing methods to produce wires for diverse purposes. However, the modernization of wire drawing processes gained momentum during the Industrial Revolution, fuelled by advancements in machinery, materials science, and engineering principles. The invention of specialized wire drawing machines in the 18th and 19th centuries revolutionized industrial manufacturing, paving the way for mass production of wires with precise dimensions and mechanical properties [3]. The wire is produced by such metal-forming processes as rolling, extrusion, drawing and their combination. Drawing is the most common method of making wire. Drawing can be carried out through monolithic, and roller dies [2, 4, 5].

Wire drawing stands out as the predominant manufacturing method employed for reducing the diameter of wires, that accomplished by pulling the wire through a die. This process imparts the desired physical and mechanical properties, such as elasticity and plasticity, while precisely defining geometric features in the resultant products. In contrast to alternative methods like rolling and extrusion, wire drawing provides superior dimensional control, enables continuous processing, incurs lower capital equipment costs, and extends its applicability to small cross-sections [6]. The efficacy of a wire drawing process hinges upon three pivotal factors within an engineering context: (a) the inherent characteristics of the raw material, (b) the die geometries, encompassing both die angle and die length, and the processing conditions, notably the drawing speed and friction at the interface between the die and the wire. Notably, with regards to the latter factor, heat generation is inherent due to the friction arising from the pressure generated during the plastic deformation [4, 5]

The technique of wire drawing involves dragging the wire through one or more drawing dies to lower the cross-section of the wire. Wire drawing has numerous uses, including the manufacture of cables, tension-loaded structural elements, paper clips, wheel spokes, and stringed musical instruments [6]. Drawing differs from extrusion, while having a similar technique. In that, the wire is dragged through the die as opposed to being pushed through it. Drawing is often done at room temperature, making it a cool working process. However, in order to lower forces, drawing may also be done at higher temperatures for big wires [7]. The effect of drawing direction on microstructure and mechanical properties in twinning-induced plasticity (TWIP) steel during wire drawing has been investigated to improve drawability for wire rod applications. It was found that the drawing direction had a significant influence on the microstructure evolution and the mechanical properties of the TWIP steel wire [4].

The combination of high cooling rate *(≈104 K/s)* during alloy solidification and high temperature before casting *(≈830 °C)* caused zirconium to dissolve almost completely in the aluminum solid solution (Al). Additions of iron and silicon were completed in the uniformly distributed eutectic Al_8Fe_2Si phase particles with an average size of less than *1 µm* [8]. This microstructure enhances the strength and ductility of the alloy, making it suitable for wire drawing applications. The alloy was subjected to a multi-pass wire drawing process with a total area reduction of *97.5%*. The wire drawing process resulted in a significant increase in the ultimate tensile strength and yield strength of the alloy, as well as a decrease in the elongation and electrical conductivity [4, 9].

The efficacy of a wire drawing process hinges upon three pivotal factors within an engineering context: (a) the inherent characteristics of the raw material, (b) the die geometries, encompassing both die angle and die length, and (c) the processing conditions, notably the drawing speed and friction at the interface between the die and the wire. Notably, with regards to the latter factor, heat generation is inherent due to the friction arising from the pressure generated during the plastic deformation [10]. This friction is directly proportional to the normal tension at the wire/die interface, resulting in the production of heat due to the relative movement between the material and the die [11]. In essence, the interplay between friction, heat generation, and material deformation plays a crucial role in shaping the dynamics of the wire drawing process [10]. The heat generation affects the temperature distribution along the wire, which in turn affects the material flow stress and the drawing force. Therefore, it is important to monitor and control the temperature of the wire during the wire drawing process to ensure the quality and efficiency of the process. One of the methods for monitoring the wire drawing process is using thermal imaging, which can capture the temperature changes of the wire as it leaves the drawing die [4].

Deep drawing stands out as a widely utilized sheet metal forming process in various industries for efficiently producing cup-shaped components at high rates. The components manufactured through deep drawing find extensive applications in aerospace, automotive, marine, beverage, and other sectors [12]. The deep drawing process involves five interconnected activities: 1) pure radial drawing between the die and blank-holder, 2) bending and sliding over the die profile, 3) stretching between the die and the punch, 4) bending and sliding over the punch profile radius, and 5) stretching and sliding over the punch face. The identification of optimal process parameter levels is crucial for ensuring the production of components with the desired quality [12]. Some of the process parameters that affect the deep drawing process are the blank-holder force, the punch force, the die clearance, the lubrication condition, and the material properties. The optimization of these parameters can be done using various methods, such as experimental design, numerical simulation, or metaheuristic algorithms. The optimization aims to minimize the defects, such as wrinkling, tearing, or spring-back, that may occur during the deep drawing process [13].

The industrial significance of wire drawing extends beyond its role as a metalworking process; it embodies a paradigm of precision engineering, innovation, and continuous improvement. Industries reliant on drawn wires rely on wire drawing as a critical enabling technology for their operations, underscoring its indispensable nature in today's interconnected global economy. From automotive manufacturers and aerospace companies to telecommunications providers and medical device manufacturers, wire drawing serves as a linchpin for innovation and progress [14]. Wire drawing enables the production of wires with various shapes, sizes, and properties, depending on the application and the customer requirements. Wire drawing also contributes to the development of new materials, such as nanocrystalline metals, shape memory alloys, or biodegradable metals, that have enhanced or novel characteristics. Wire drawing is a dynamic and evolving field that requires constant research and development to meet the challenges and demands of the modern world [2].

The current article will present a general wire drawing process, schematic review for the wire drawing, material methods, experimental procedure, experimental and numerical results with design of experiments, and conclusions.

2. Wire Drawing Process

The mother coil is a large spool of wire that can weigh up to several tons and has a diameter of up to 2.5 meters. The Snarl Stop Switch is a device that detects any loops or knots in the wire and stops the machine automatically to avoid damage or waste. The wire then progresses to the De-Scaling Unit, where impurities such as rust, scale, or dirt are removed, leaving the wire clean and shiny [15-18]. The De-Scaling Unit uses mechanical or chemical methods to clean the wire, such as wire brushing, sand blasting, acid pickling, or ultrasonic cleaning. The Brushing Unit follows, refining the wire’s surface with specialized brushes, enhancing its quality for the next steps [15-18]. The Brushing Unit removes any remaining impurities or roughness from the wire and improves its adhesion to the coating material. Rinsing cleans the wire before it enters the Borax Tank, where it’s coated for lubrication and protection. The Borax Tank is a container filled with a hot solution of borax, which is a salt of boric acid [15-18]. The borax coating acts as a lubricant and a flux, reducing the friction and the oxidation during the drawing process. The Hot Blast Unit softens the wire for the Draw Dies, where it’s stretched and reduced in diameter. The Hot Blast Unit is a furnace that heats the wire to a temperature of about 800°C, making it more ductile and malleable. The Draw Dies are metal molds with tapered holes that shape the wire into the desired size and cross-section [15-18]. The wire is pulled through the Draw Dies by a motorized capstan, which applies a tensile force on the wire. The number and size of the Draw Dies depend on the final diameter and shape of the wire [15-18].

The Drum & Dancer Roller controls tension, cooling, and speed, allowing precise winding at the Spooler or Drop Coiler, see Fig. 1.

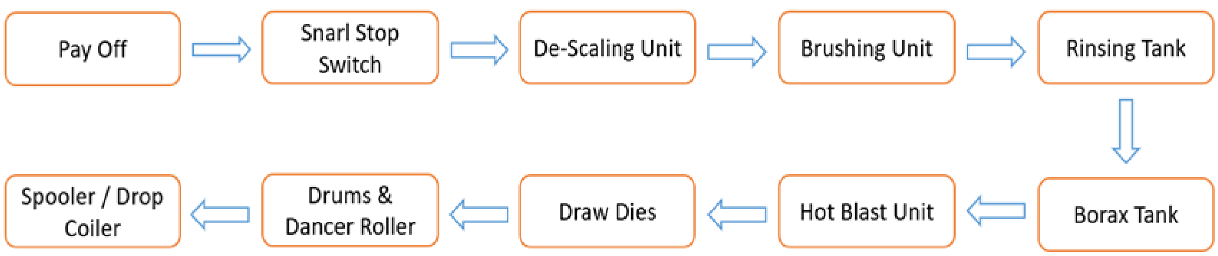


Fig. 1. Flow chart of wire drawing machine.

After the intricate wire drawing process, the wire undergoes testing for quality assurance. The tensile testing phase evaluates its mechanical properties, especially tensile strength. This crucial step ensures the wire meets the highest standards for its intended applications. The entire journey, from the Snarl Stop Switch to tensile testing, exemplifies precision engineering and craftsmanship, transforming raw wire into a refined product ready for diverse uses [19].

3. Schematic review

This paper presents a systematic review of literature focusing on the wire drawing process as a crucial technique in mechanical and industrial operations. The study aims to identify the uses, applications, and significance of wire drawing in manufacturing, with a specific focus on the techniques, tools, and methods employed to enhance mechanical and industrial processes, resulting in the production of wires with improved properties and reduced defects. The authors selected 69 papers from renowned publishers MDPI, Springer, and Elsevier, conducting electronic database searches from 2010 to 2023. Initially identifying 172 potentially relevant articles, the researchers eliminated 21 duplicates and excluded 82 based on title and abstract reviews for irrelevance. The remaining 69 full-text documents were thoroughly reviewed and analyzed. The analysis is indicated in Fig. 2.

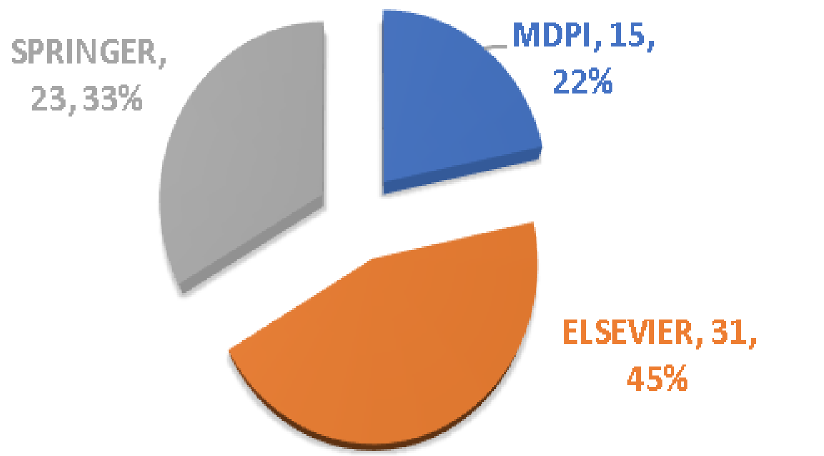


Fig. 2. Publishing House

Most papers on wire drawing appear to be published by Elsevier, at 46%. Springer is the second most popular publishing house within the literature reviewed on wire drawing research papers at 33%. MDPI publishing house appears to have the lower rate of wire drawing papers within the literature reviewed, at 21%.

There has been a relatively consistent level of research on wire drawing over the past decade, with the number of articles published each year ranging from 2 to 8. There is a slight increase in the number of articles published in 2013, with 8 articles published that year. The number of articles published appears to have remained relatively stable from 2014 to 2021, with 4 to 7 articles published each year. The number of articles in each year is seen in Fig. 3.

The reviewed literature primarily focused on several parameters related to wire drawing processes. The temperature of the dies was the most discussed aspect, comprising 23% of the literature, followed by the tensile strength of the material at 21.7%, and drawing speed at 17.4%. Other parameters considered included lubrication (10.6%), die sequence (6.2%), surface finish of the wires after drawing (2.5%), and 0.6% of the literature reporting pellet size to enhance dies' lifespan. In terms of research methodologies, experimental techniques were prevalent in 11 articles, with 27 articles combining experimentation with microstructure analysis. The Fig. 4. Shows all the parameters used in our study.

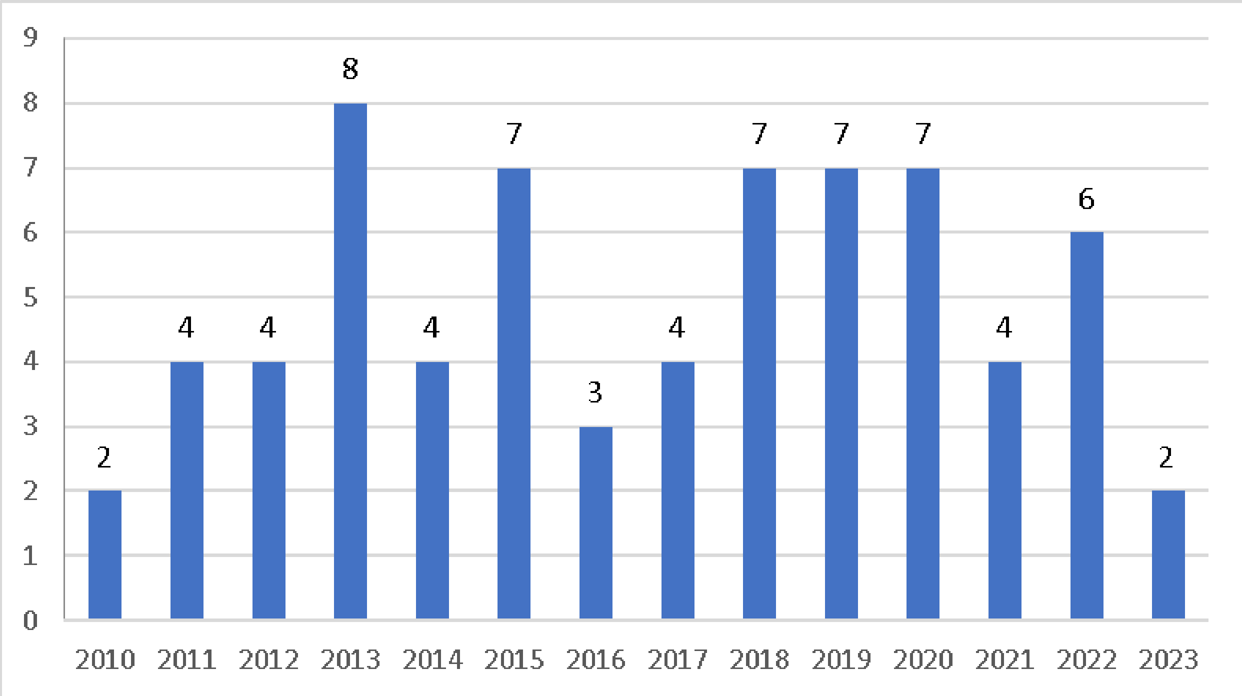


Fig.3. Published articles per year.

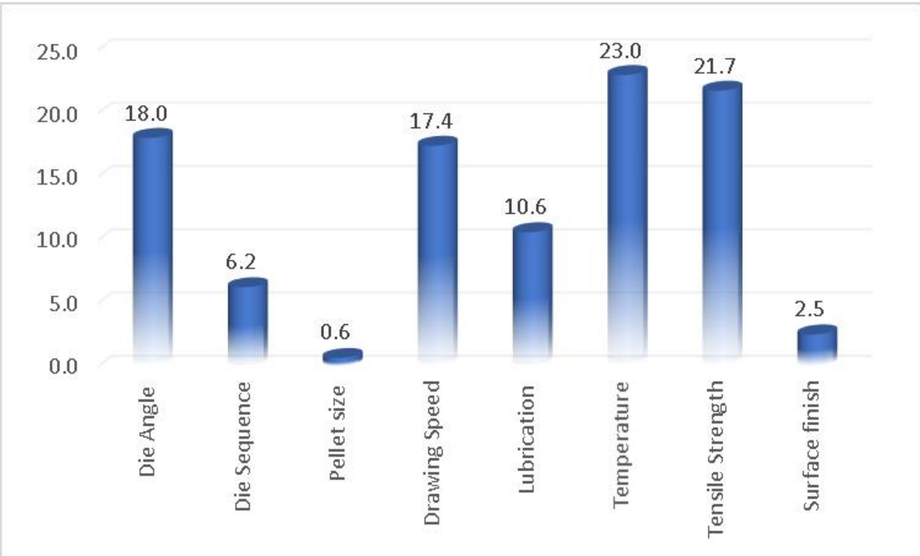


Fig. 4. Parameters of the wire drawing.

A combination of experimental and numerical methods was evident in 5 articles, while 14 articles employed a triad of experimental, numerical, and microstructural analyses. A unique fusion of experimental, thermal imaging, and microstructural studies was featured in one article. Mathematical analysis, either standalone or combined with numerical methods, was present in 3 articles, and microstructural studies alone were highlighted in 2 articles. Additionally, 5 articles exclusively utilized numerical methodologies, demonstrating the diverse landscape of methodologies in materials research and the varied approaches employed in scholarly investigations. All of these methods are explained in Fig. 5.

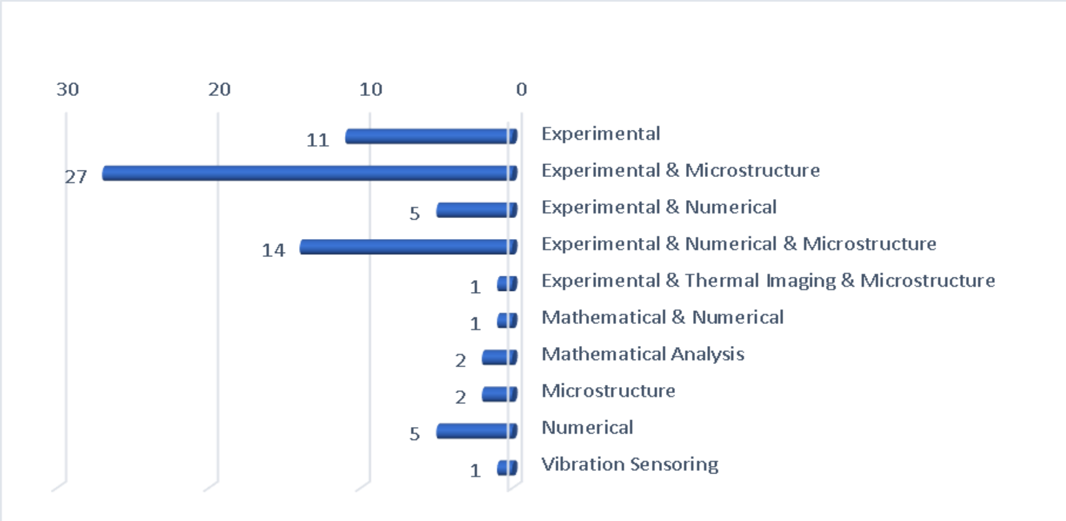


Fig. 5. Methods used in comparative studies.

Based on the data presented in Fig. 6, the most studied materials in the context of wire drawing are high-carbon steel (HCS) with 10 articles [20-25] and low carbon steel (LCS) also with 10 articles [26-30]. The preference for these materials is attributed to high-carbon steel's strength, resistance properties, and moderate ductility, facilitating increased drawing speed without wire-breaks or quality deterioration. Low carbon steel's popularity stems from its malleability, ductility, availability, and ease of processing, making it suitable for high-strength wire production without additional treatments. Medium-carbon steel (MCS) follows with 8 articles, while TWIP steel has 7 articles. Other materials studied include copper (4 articles), eutectoid steel (3 articles), hot-dip steel, and LCS, HCS, and TWIP steel (2 articles each), and prestressing steel (2 articles), with various materials studied in only one article each.

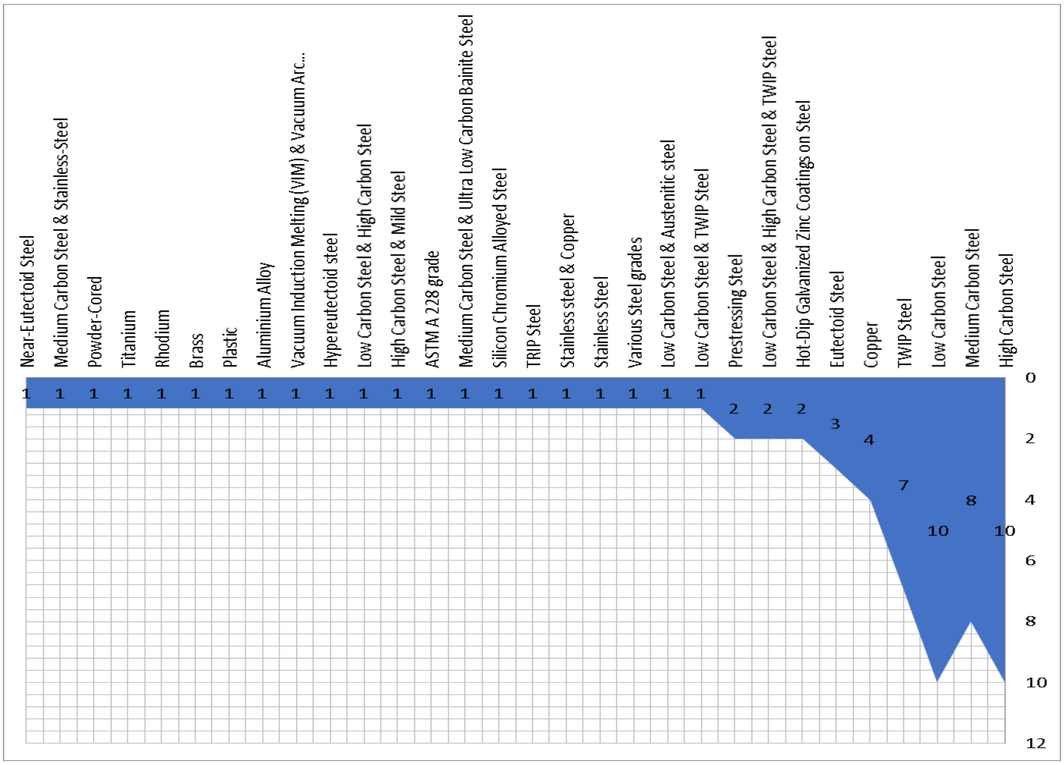


Fig.6. Materials used in various studies supplied in our research.

4. Materials and methods

Through the previous literature of wire drawing process and the company case study, the factors expected to affect the product were identified, including three main factors (die angle, drawing speed, and lubricant type), with three different levels for each factor, resulting in a total of 27 runs. As seen in fig. 7.a and fig. 7.b. in the supplementary data. Table 1. Shows the entire design of experiment (DOES).

In the study the CHENG-I WIRE MACHINERY CO. LTD. Machine has been selected, specifically Machine No. 9. This choice was made due to its new condition and the excellent state of all its components. Moreover, it offers us the advantage of full control over the machine during our experiments.

Table 1. Design of Experiments (DOE).

No. of Experiment	Design Of Experiments			Average Tensile Strength N/mm^2
	Die angle (Degree◦)	Speed (M/min)	Lubricant	
1	10	400	L1	1548.5
2	10	400	L2	1571
3	10	400	L3	1565
4	10	500	L1	1570
5	10	500	L2	1584.5
6	10	500	L3	1565.5
7	10	600	L1	1595.5
8	10	600	L2	1641
9	10	600	L3	1584.5
10	12	400	L1	1562.5
11	12	400	L2	1585
12	12	400	L3	1542.5
13	12	500	L1	1568.5
14	12	500	L2	1570
15	12	500	L3	1543
16	12	600	L1	1569
17	12	600	L2	1575.5
18	12	600	L3	1566
19	14	400	L1	1526.5
20	14	400	L2	1560
21	14	400	L3	1529.5
22	14	500	L1	1558
23	14	500	L2	1549
24	14	500	L3	1557
25	14	600	L1	1554.5
26	14	600	L2	1579
27	14	600	L3	1559.5

Table 2. Chemical composition %

	C	Si	Mn	P	S	Cr	Ni	CU	N
HEAT NO.	2	2	2	3	3	2	2	2	4
				$2 = 10^{-2}$ $3 = 10^{-3}$ $4 = 10^{-4}$					
T290107621	66	18	63	14	11	3	2	3	41

Regarding selection of wire, we chose Grade 1066 wire, As shown in table 2 above, I used SHAGANG, for our experiments due to its consistent mechanical properties as shown in the table above. It has a tensile strength of 962 MPa and a uniform diameter of 5.5 mm. To keep the results of our experiments, correct, we fixed the heat number of the wire to be constant throughout all experiments. This choice of wire, with its robust tensile strength and uniform dimensions, not only met our experimental criteria but also instilled confidence in the stability of its mechanical properties during our testing, thus ensuring the accuracy and reliability of our wire drawing experiments.

In the experiments, the pallet size was adjusted from 15x13 to 17x15 for each tungsten carbide drawing die, resulting in enhanced stability, reduced wear, increased throughput, improved wire quality, and greater versatility.

This modification was prompted by observations from wire drawing machines. Die angle variation involved selecting angles of 10, 12, and 14 degrees, with each angle undergoing grinding and polishing processes to ensure smooth0 and uniform surfaces. Die angles were controlled using a steel needle operated on the Bremer machine. Wire drawing speeds ranged from 400 to 600 M/min, chosen to assess speed impacts on the process. Four types of lubricants were tested exclusively for different dies, and experiments included three lubricant combinations (L1: S612, S1440; L2: S39, S940; L3: S39, S1440) to examine their effects comprehensively. Table 3 details specifications of the lubricants used. The supplied Fig.7. and diagram in Fig. 8. show size and dimensions of pallets used in experiments.

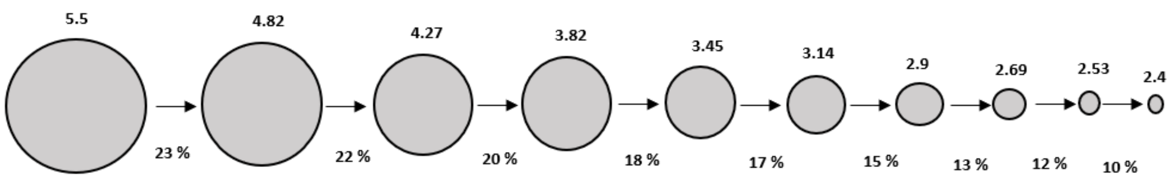
Table 3. Lubricant Specifications.

Specification	Type and color	Gravity	Moisture	Chemical composition	Cas No	Wt.%
PANLUBE S 39	granulated powder	0.8 – 1.0 (g/cm3),	<2%	Calcium Stearate	66071 – 81 – 6	25 – 40 %,
				Calcium Hydroxide	1305 – 62 – 0	30 – 50 %,
				Inert Mineral Additives	-	15 – 30%,
				Calcium Sulphate	10101 – 41 – 4	5 – 15%.
PANLUBE S 612	white yellowish powder	0.80 – 1.0 g/cm3	<2% max	Calcium Stearate	66071 – 81 – 6	25 – 35%,
				Calcium hydroxide	1305 – 62 – 0,	50 – 60%
				Inert Mineral Additives	-	5 – 15%.
PANLUBE S 1440	granulated white powder	0.60 – 0.80 g/cm3	< 3%.	Sodium Stearate	822 – 16 – 2	85 – 95
				Sodium Carbonate	497 – 19 – 8	2 – 10
				Borax Pentahydrate	12179 – 04 – 3	2 – 10
PANLUBE S 940	granulated powder	0.70 – 0.90 g/cm3	2%	Sodium Stearate	822 – 16 – 2	50 – 70%,
				Inert Mineral Additives	-	25 – 40%,
				Borax Pentahydrate	12179 – 04 – 3	2 – 10%
				Sodium salts	-	5 – 15%.

5. Experimental procedure:

In wire drawing, the process of reducing the cross-sectional area of a wire. This process begins with a wire of a certain diameter, and through a series of drawing steps, the wire's diameter is reduced, leading to a decrease in its cross-sectional area. To achieve the desired reduction from high to low, as shown in the figure, 23% to 10%, Eq (1) is used to compute RA per pass.

$$RA = \frac{A_o - A_f}{A_o} \times 100(\%) \quad (1)$$



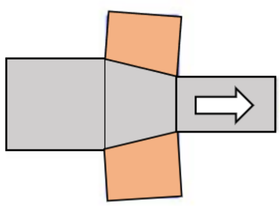


Fig. 10. The wire passing through the wire drawing machines.

6. Results

In this study, we investigate the effects of machine speed and die angle on tensile strength across different lubricants (Lubricant L1, L2, and L3) in the wire drawing process.

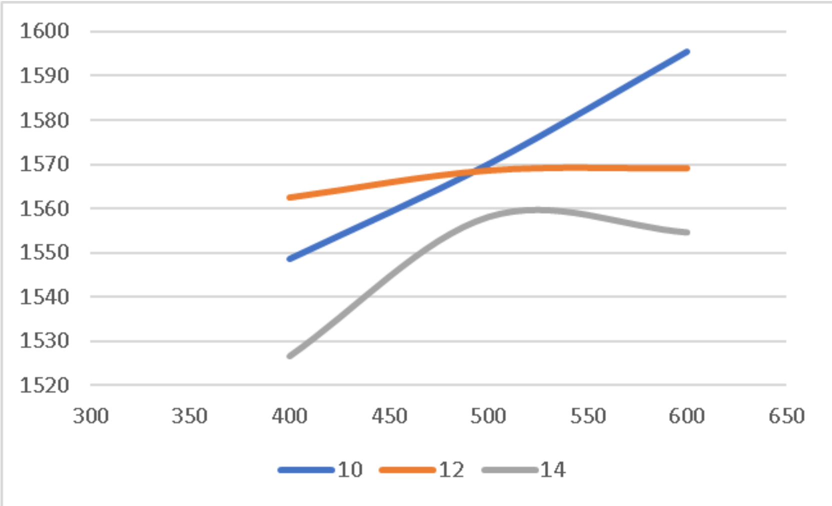


Fig. 11. Average Tensile Strength for Lubricant L1

The average tensile strength (in MPa) of a wire produced by a drawing process using lubricant L1, under different combinations of die angle and machine speed is shown in Fig. 11. The die angle is the angle of the conical part of the die that shapes the wire, and the machine speed is the rate at which the wire is pulled (in m/min). The data suggests that the tensile strength increases with the machine speed for a fixed die angle, and decreases with the die angle for a fixed machine speed. The highest tensile strength (1595.5 MPa) is achieved when the die angle is 10 degrees and the machine speed is 600 m/min. The lowest tensile strength (1526.5 MPa) is achieved when the die angle is 14 degrees and the machine speed is 400 m/min.

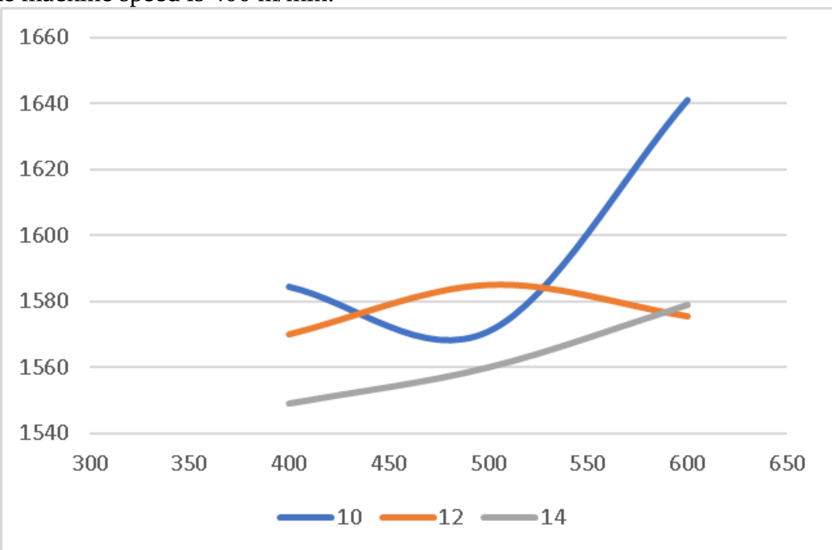


Fig. 12. Average Tensile Strength for Lubricant L2

In Fig. 12, the tensile strength increases with the machine speed for a die angle of 10 degrees, but decreases for a die angle of 12 degrees, and shows no clear trend for a die angle of 14 degrees. Similarly, the tensile strength decreases with the die angle for a machine speed of 400 m/min, but increases for a machine speed of 600 m/min, and shows no clear trend for a machine speed of 500 m/min. The highest tensile strength (1641 MPa) is achieved when the die angle is 10 degrees and the machine speed is 600 m/min. The lowest tensile strength (1549 MPa) is achieved when the die angle is 14 degrees and the machine speed is 400 m/min. The figure indicates that the lubricant L2 does not provide a uniform effect on the tensile properties of the wire, and that the optimal process parameters depend on the interaction between the die angle and the machine speed.

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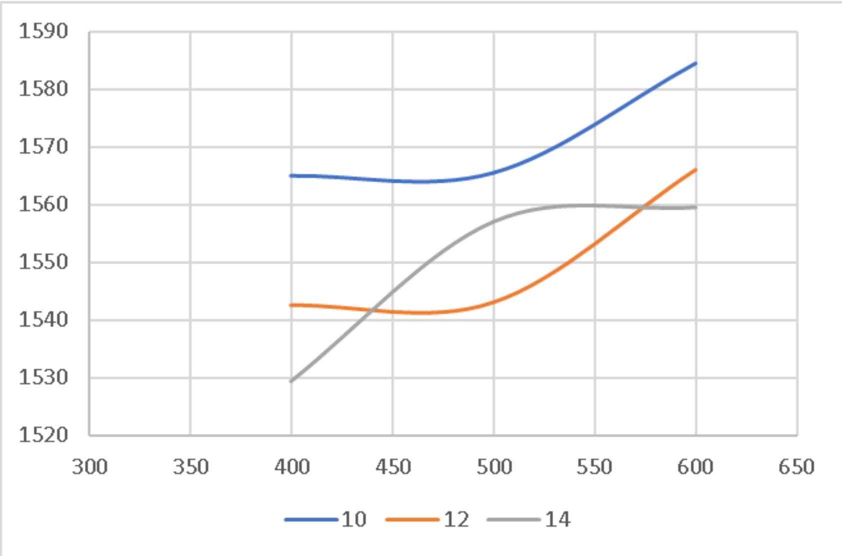

Fig. 13. Average Tensile Strength for Lubricant L3

It is illustrated in Fig. 13 that the tensile strength generally increases with the machine speed and decreases with the die angle, but the changes are not very significant. The highest tensile strength (1584.5 MPa) is achieved when the die angle is 10 degrees, and the machine speed is 600 m/min. The lowest tensile strength (1529.5 MPa) is achieved when the die angle is 14 degrees, and the machine speed is 400 m/min. The figure indicates that the lubricant L3 provides a consistent effect on the tensile properties of the wire, and that the optimal process parameters are the lowest die angle and the highest machine speed.

7. Multilevel Factorial Design

In this analysis of variance (ANOVA) for a general factorial regression model studying the relationship between tensile strength and die angle, drawing speed, and lubrication, several key findings emerge. The model as a whole demonstrates statistical significance ($F(18, 8) = 4.49$, $p = 0.018$) with a substantial proportion of variance explained (90.99%). Specifically, the linear component of the model is highly significant ($F(6, 8) = 10.73$, $p = 0.002$), attributing 72.51% of the variance to the main effects of die angle, drawing speed, and lubrication. Individually, die angle ($F(2, 8) = 12.35$, $p = 0.004$), drawing speed ($F(2, 8) = 10.99$, $p = 0.005$), and lubrication ($F(2, 8) = 8.84$, $p = 0.009$) significantly influence tensile strength. However, the two-way interactions between these factors do not show statistically significant effects ($F(12, 8) = 1.37$, $p = 0.336$), indicating that the combined effects of these factors are not significantly different from what would be expected based on their individual effects. Overall, the model provides a strong fit to the data, explaining nearly 91% of the variance, with a relatively low prediction error (PRESS = 13149.2) and model selection criteria (AICc = 358.02, BIC = 243.94), underscoring its utility in understanding the relationship between process variables and tensile strength in this context as shown in table 4, and fig. 14 and fig. 15.

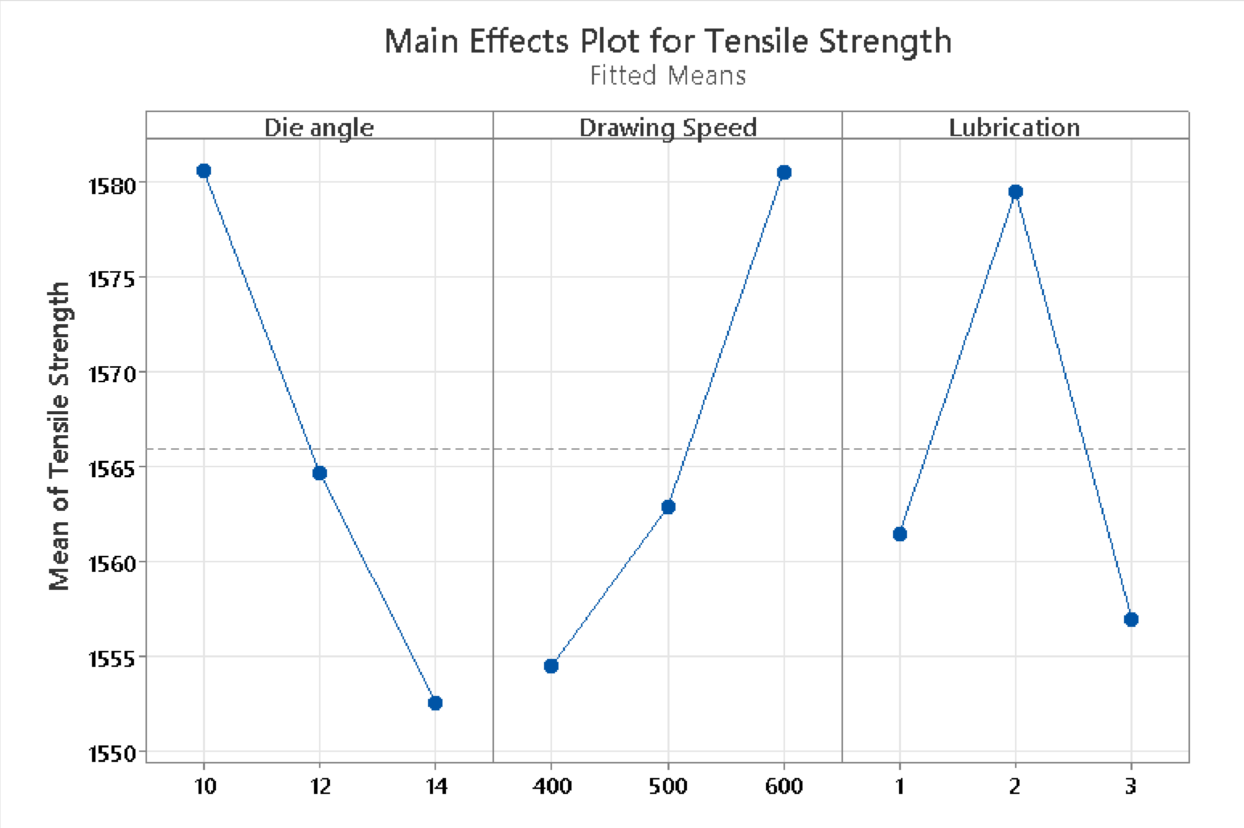

Fig. 14. The general main effects plot for tensile strength between die angle, drawing speed, and lubrication.

Table 4. Analysis of Variance (General Factorial Regression: Tensile Strength versus Die angle, Drawing Speed, Lubrication)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	18	11655.8	90.99%	11655.8	647.5	4.49	0.018
Linear	6	9288.2	72.51%	9288.2	1548.0	10.73	0.002
Die angle	2	3564.1	27.82%	3564.1	1782.0	12.35	0.004
Drawing Speed	2	3172.7	24.77%	3172.7	1586.3	10.99	0.005
Lubrication	2	2551.5	19.92%	2551.5	1275.8	8.84	0.009
2-Way Interactions	12	2367.6	18.48%	2367.6	197.3	1.37	0.336
Die angle*Drawing Speed	4	1327.4	10.36%	1327.4	331.9	2.30	0.147
Die angle*Lubrication	4	469.3	3.66%	469.3	117.3	0.81	0.551
Drawing Speed*Lubrication	4	570.8	4.46%	570.8	142.7	0.99	0.466
Error	8	1154.4	9.01%	1154.4	144.3		
Total	26	12810.2	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
12.0124	90.99%	70.71%	13149.2	0.00%	358.02	243.94

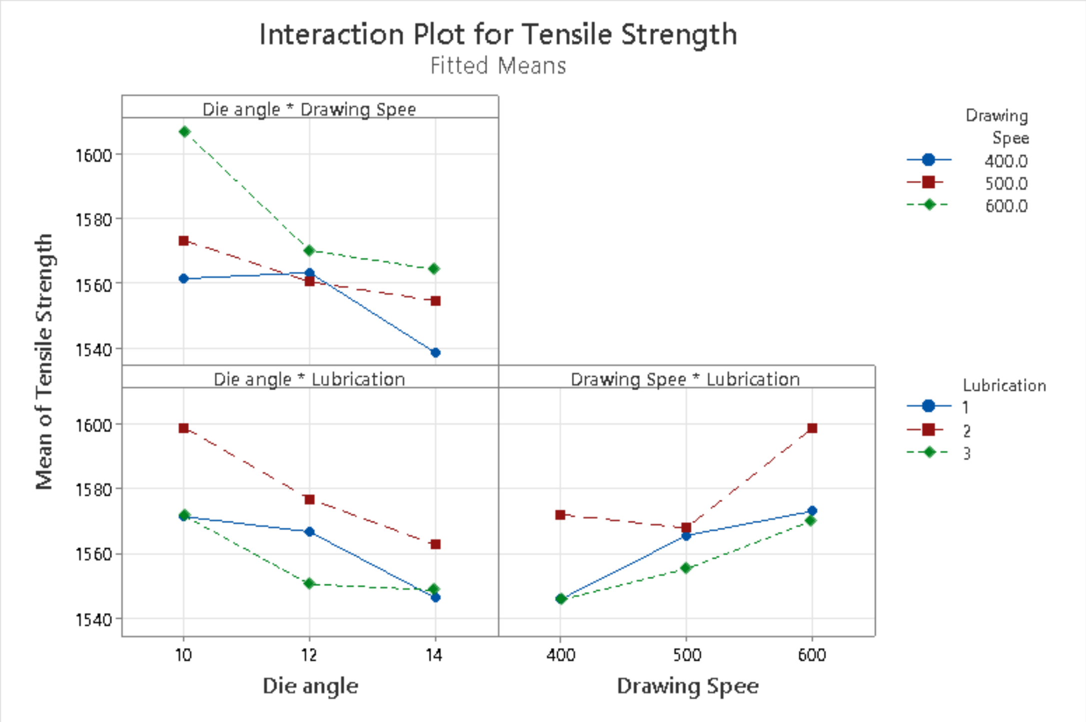

Fig. 15. General interaction plot for tensile strength in die angle and drawing speed.

Lubricant L1

Firstly, the model demonstrates a moderate degree of explanatory power, with an R-squared value of 80.34%, indicating that 80.34% of the variability in tensile strength can be explained by the variables under consideration. However, when adjusted for the number of predictors in the model, the adjusted R-squared drops to 60.68%, suggesting a more conservative estimate of the model's explanatory capability. The significant F-values (4.09, 3.87, and 4.31) corresponding to die angle and drawing speed indicate that these factors individually contribute to explaining the variation in tensile strength, though their p-values (0.116 and 0.101, respectively) suggest that these effects may not be statistically significant at conventional significance levels. The linear term within the model also fails to reach statistical significance ($p = 0.101$), implying that the relationship between the predictors and tensile strength may not be strictly linear.

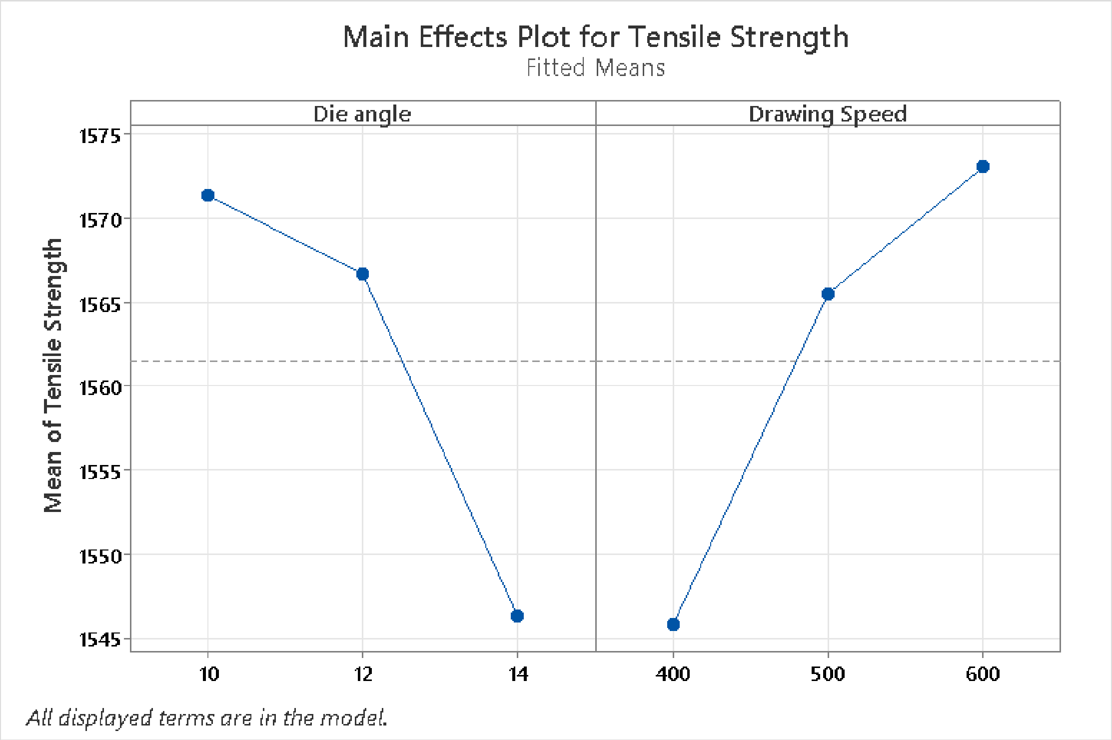

Fig. 16. The Lubricant L1 main effects plot for tensile strength between die angle, drawing speed, and lubrication.

Table 5. Analysis of Variance ((l1): General Factorial Regression: Tensile Strength versus Die angle, Drawing Speed)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	2241.3	560.3	4.09	0.101
Linear	4	2241.3	560.3	4.09	0.101
Die angle	2	1060.2	530.1	3.87	0.116
Drawing Speed	2	1181.1	590.5	4.31	0.101
Error	4	548.4	137.1		
Total	8	2789.7			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
11.7094	80.34%	60.68%	0.47%

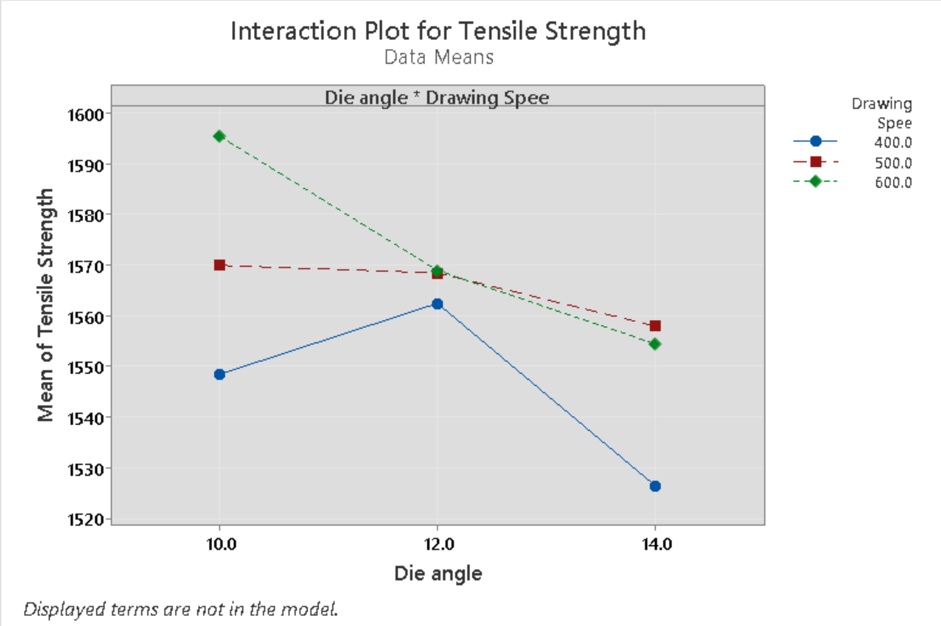

Fig. 17. Lubricant 1 plot for tensile strength in die angle and drawing speed.

Lubricant L2

The model accounts for 68.57% of the total variation in tensile strength, indicating a substantial influence of the predictors. Specifically, die angle and drawing speed individually contribute 37.41% and 31.16% to the model, respectively. However, when examining the effects of these factors individually, neither die angle nor drawing speed show statistically significant impacts on tensile strength, as evidenced by their relatively high p-values (0.208 and 0.252, respectively). The residual error, representing unexplained variability, contributes to 31.43% of the total variance, suggesting that other factors not included in the model may influence tensile strength. The model's summary statistics further confirm its explanatory power, with a substantial adjusted R-squared value of 37.15%.

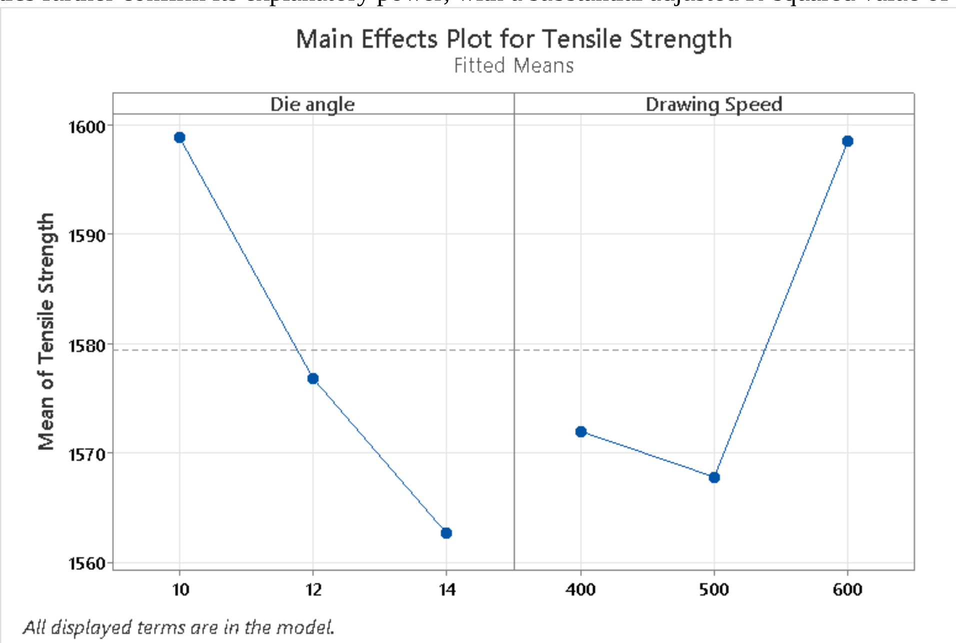

Fig. 18. The Lubricant L2 main effects plot for tensile strength between die angle, drawing speed, and lubrication.

Table 6. Analysis of Variance ((l2): General Factorial Regression: Tensile Strength versus Die angle, Drawing Speed)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	3653	68.57%	3653	913.2	2.18	0.234
Linear	4	3653	68.57%	3653	913.2	2.18	0.234
Die angle	2	1993	37.41%	1993	996.4	2.38	0.208
Drawing Speed	2	1660	31.16%	1660	830.0	1.98	0.252
Error	4	1674	31.43%	1674	418.5		
Total	8	5327	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
20.4569	68.57%	37.15%	8474.34	0.00%	126.57	85.76

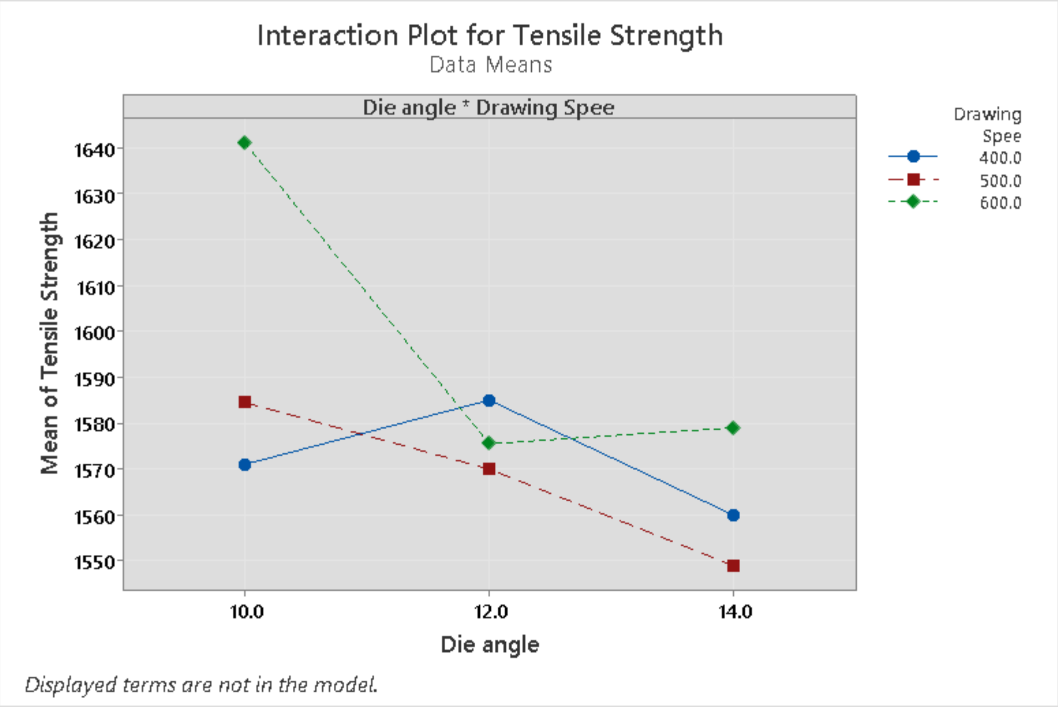

Fig. 19. Lubricant 2 plot for tensile strength in die angle and drawing speed.

Lubricant L3

The model exhibits a high degree of explanatory power, with the overall model explaining 87.89% of the variance in Tensile Strength. Both Die angle and Drawing Speed show substantial contributions to the model, with Die angle alone explaining 45.77% of the variance and Drawing Speed explaining 42.12%. The F-values associated with these predictors are statistically significant at $p < 0.05$, indicating that these factors have a significant impact on Tensile Strength. The model's R-squared value of 87.89% suggests that nearly 88% of the variability in Tensile Strength can be explained by the variables included in the model.

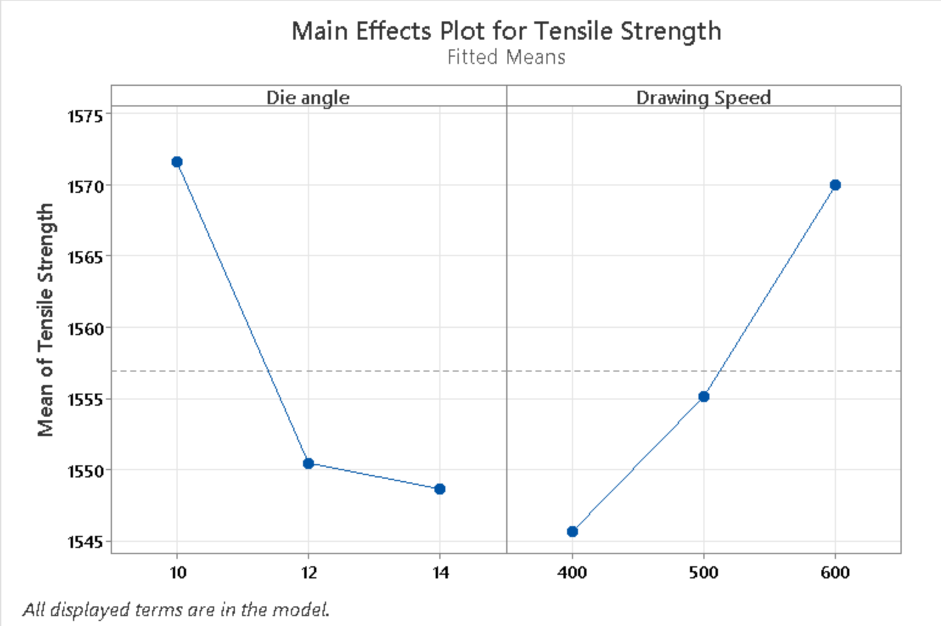

Fig. 20. The Lubricant L3 main effects plot for tensile strength between die angle, drawing speed, and lubrication.

Table 7. Analysis of Variance ((l3): General Factorial Regression: Tensile Strength versus Die angle, Drawing Speed)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	1882.8	87.89%	1882.8	470.69	7.26	0.040
Linear	4	1882.8	87.89%	1882.8	470.69	7.26	0.040
Die angle	2	980.4	45.77%	980.4	490.19	7.56	0.044
Drawing Speed	2	902.4	42.12%	902.4	451.19	6.96	0.050
Error	4	259.4	12.11%	259.4	64.86		
Total	8	2142.2	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
8.05364	87.89%	75.78%	1313.44	38.69%	109.79	68.98

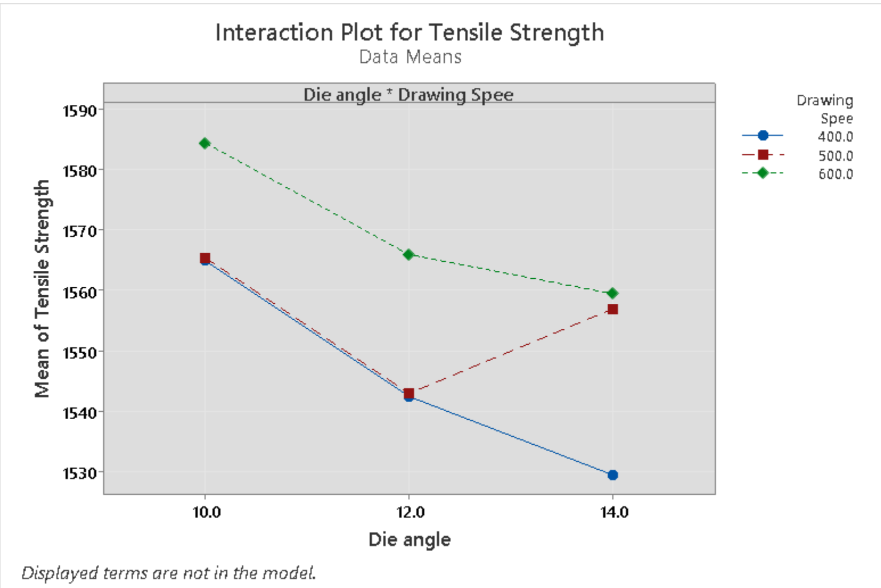

Fig. 21. Lubricant 3 plot for tensile strength in die angle and drawing speed.

8. Conclusions:

In conclusion, this study has provided valuable insights into the wire drawing process and its significance in manufacturing. Through a comprehensive investigation employing various methodologies such as experimental, numerical, and mathematical analyses, we have gained a deeper understanding of the factors influencing wire drawing outcomes. By examining the effects of die angle, drawing speed, and lubricant type on wire properties, we have identified key parameters that significantly impact tensile strength and overall wire quality. The findings underscore the importance of precision control over process variables to achieve desired outcomes consistently. Moreover, statistical analyses have revealed substantial relationships between process variables and tensile strength, offering insights into optimizing wire drawing processes for enhanced efficiency and productivity. This research not only advances our understanding of wire drawing processes but also provides practical insights for improving wire manufacturing techniques across various industries. Moving forward, further research can explore additional factors influencing wire drawing outcomes and develop advanced methodologies to further enhance wire properties and production efficiency. Ultimately, these efforts will contribute to advancing wire manufacturing technologies, reducing defects, and meeting the evolving demands of modern industrial applications.

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