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Effect of Drawing Speed on the Reliability of Drawing Dies

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Abstract

Reliable drawing dies are crucial for successful modern wire production. If these parts fail, repairs can be time-consuming and costly. This study examines how drawing speed affects die reliability within a standard commercial range of 50 to 400 m/min. We tested 750 tungsten carbide dies using various methods, including Weibull reliability analysis. Fifty dies were tested at each of 15 different speeds. Our results show a strong inverse relationship between die lifespan and drawing speed, and a significant direct relationship between operating temperature and wear rate. As drawing speed increased from 50 to 400 m/min, the average die life decreased by 65%, the wear rate increased exponentially, and the average operating temperature rose linearly. We identified three failure zones: a moderate wear phase (50–150 m/min), a rapid failure stage (300–400 m/min), and a period of accelerated degradation (150–300 m/min). In each zone, different wear mechanisms may occur. These findings help manufacturers extend die life, improve efficiency, implement predictive maintenance, and develop new die technologies that could reduce costs by 15–25%.

Keywords: *Drawing dies, Wire drawing, Reliability analysis, Drawing speed, Wear mechanisms, Tungsten carbide*

1. Introduction

1.1. The Industrial Landscape and Its Economic Stakes

When you consider the sheer scale of the global wire drawing industry—we're talking about a $15 billion annual market here—it becomes clear just how fundamental this sector is to modern manufacturing [1, 3]. Think about it: virtually every electrical grid, automotive system, telecommunications network, and medical device you encounter relies on precisely drawn wire components. It's one of those industries that operates largely behind the scenes, yet our entire technological infrastructure would collapse without it.

The wire drawing process itself is fascinating from an engineering perspective. What we're essentially doing is taking raw material and forcing it through progressively smaller dies to achieve exact dimensional tolerances and surface finish requirements. Sounds straightforward enough, right? But here's where things get complicated: those drawing dies—the heart of the entire operation—endure absolutely punishing conditions [2, 11]. We're talking about immense mechanical stress, elevated temperatures, and relentless friction, all happening simultaneously. It's a testament to materials science that these components work at all, let alone enable the high-speed production that modern manufacturing demands [10, 26].

Now, here's what keeps plant managers awake at night: die failures. And I'm not exaggerating when I say this is a massive problem. These failures account for somewhere between 35 and 45 percent of all downtime in contemporary wire manufacturing facilities [19]. When a die fails, it's rarely just a simple replacement job. Instead, you get this domino effect—production grinds to a halt, product quality gets compromised, raw materials go to waste, and suddenly you're looking at expensive emergency repairs that nobody budgeted for [8].

The financial implications are staggering when you really dig into the numbers. Conservative estimates suggest that die-related failures cost the global wire industry approximately $2.3 billion every year [20]. And that's just the direct costs—we're not even talking about the indirect damage like delayed shipments, frustrated customers, and the long-term erosion of business relationships that inevitably follow production disruptions.

What makes this situation even more challenging is the relentless pressure for faster production speeds and tighter quality specifications [21, 22]. Market demands keep pushing manufacturers to run their equipment harder and faster, which naturally puts even more stress on these already-stressed components. It's a classic engineering dilemma: how do you increase performance while maintaining reliability? The stakes couldn't be higher, because in today's competitive manufacturing environment, the companies that solve this puzzle will have a significant advantage over those that don't.

1.2. A Look at the Technology and Materials

Tungsten carbide (WC-Co) dies are the industry standard due to their exceptional hardness (1800–2000 HV), wear resistance, and thermal stability [6, 7]. Their performance is due to their microstructure, which consists of hard tungsten carbide particles in a tough cobalt (Co) binder [28]. However, even these advanced materials are not immune to the relentless strain of high-speed drawing [3]. The process subjects the dies to a combination of mechanical tension, thermal cycling from friction, and abrasive effects from continuous sliding [24, 25]. As drawing speeds increase, these forces intensify and interact in complex ways, accelerating the degradation process and shortening the die's useful life [11, 12]. A deeper understanding of these interactions is essential for optimizing machine parameters and improving die designs [13, 14].

1.3. Reviewing the Field and Identifying Gaps

Researchers have long studied die performance and failure. Early work by Wistreich [1] provided a theoretical foundation for understanding the complex interactions between the die and the wire. Dieter and Bacon [4] expanded on this by exploring the physics of metal forming, with a focus on heat and friction. More recent studies have examined specific factors, such as the work by Suliga et al. [6] on how temperature affects die wear, and Hollinger et al. [7] on wear mechanisms in tungsten carbide dies. These studies have advanced our understanding of the field.

Despite this progress, there are still significant gaps in our knowledge. Much of the existing research has been limited to narrow speed ranges, which do not fully capture what happens in real-world industrial settings [15]. Studies have also tended to examine variables in isolation, overlooking the complex interplay of factors that determine die reliability [16]. A notable gap has been the lack of practical, predictive models that can be easily applied on the factory floor [17]. Additionally, many past investigations have not used the level of statistical rigor needed to generate reliable and actionable insights [18]. This study was designed to address these gaps by conducting a comprehensive and statistically robust analysis of how drawing speed affects die reliability.

1.4. Our Innovative Approach

To address these challenges, our research incorporated several new ideas:

- **Full-Spectrum Speed Analysis:** We conducted a systematic study across the entire industrial speed range (50-400 m/min), using enough data points to identify critical transition zones and define different failure patterns [11, 26].
- **Integrated, Multi-Parameter Modeling:** We developed models that link the thermal, mechanical, and tribological (wear-related) factors, providing a more complete picture of how they interact to affect die performance under different conditions [12, 13].
- **Advanced Statistical Techniques:** We used powerful methods like Weibull reliability analysis to build predictive models that are robust enough for real-world industrial use [5, 16].
- **Industry-Validated Framework:** We grounded our lab results in reality by comparing them with industry case studies, ensuring our models are not just academically interesting but also practically useful and economically relevant [35, 36].

1.5. Research Goals and Hypotheses

1.5.1. Primary Goal

Our main goal was to establish clear, quantitative links between drawing speed and the reliability of tungsten carbide dies. The ultimate aim was to use this knowledge to create predictive models that can help optimize industrial processes and improve maintenance planning [19, 39].

1.5.2. Core Hypothesis

We hypothesized that increasing the drawing speed would negatively affect the lifespan and reliability of the dies, primarily due to faster wear and higher operating temperatures [6, 11].

2. Methodology

2.1. The Experimental Setup

Our experiments were performed on a custom-built wire drawing machine designed for high precision, with a speed control resolution of 0.1 m/min (±0.05% accuracy), a maximum drawing force of 5000 N (±0.1% accuracy), and a force measurement resolution of 0.1 N (±0.05% accuracy). The machine's 200.0 mm capstan was powered by a 15 kW motor and controlled by a Siemens S7-1500 system, ensuring precise and repeatable test runs. For each of the 15 speed settings (from 50 to 400 m/min in 25 m/min increments), 50 individual tungsten carbide dies were tested, for a total of 750 dies. The wire material was high-carbon steel (AISI 1070) with an initial diameter of 2.0 mm and a surface roughness (Ra) of 0.8 μm. The dies had a semi-angle of 6° and a bearing length of 0.5 mm. A commercial oil-in-water emulsion lubricant was applied via a pressurized circulation system at a flow rate of 5 L/min. Data from the 50 dies at each speed setting were averaged to calculate aggregated mean values and confidence intervals.

2.2. Measurement Systems

- **Die Life Monitoring:** A Keyence LS-7000 series laser micrometry system was used for automated, continuous measurement of the wire's diameter. With a 0.1 μm resolution and 1000 Hz sampling rate, the system could instantly detect a failure, defined as any deviation greater than ±0.01 mm from the target diameter [24].

- **Temperature Tracking:** K-type thermocouples were placed 2 mm from the die surface inside the holder and linked to a National Instruments cDAQ-9178 data acquisition system, which recorded temperatures with an accuracy of ±0.1°C at a rate of 1000 Hz [10].
- **Wear Rate Analysis:** A Coordinate Measuring Machine (CMM) with 0.5 µm accuracy was used for precise before-and-after dimensional checks. A Mitutoyo Surftest SJ-410 profilometer with a resolution of 0.01 µm was used for a more detailed look at wear patterns [27].

2.3. Experimental Protocol

2.3.1. Preparation and Setup

To ensure consistency and eliminate external variables, each test began with a strict preparation protocol:

1 **Initial Check:** Dies were visually and dimensionally inspected with an optical microscope and CMM.

2 **Cleaning:** A 10-minute ultrasonic cleaning in acetone was followed by an isopropyl alcohol rinse.

3 **Mounting:** Dies were mounted in certified fixtures, with concentricity confirmed to be within ±0.002 mm.

4 **Baseline Measurement:** A full set of initial measurements was taken, including diameter, angle, and surface roughness.

5 **Final Verification:** A final alignment check was performed, and torque settings were verified.

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2.3.2. Test Execution

Each test followed a standardized five-phase sequence:

- **Phase 1 - Calibration (30 min):** All measurement systems were verified, ambient conditions were recorded, the equipment was warmed up, and the data acquisition system was initialized.
- **Phase 2 - Thermal Stabilization (15 min):** The system was run at 25% of the target speed to reach a stable operating temperature.
- **Phase 3 - Speed Ramp-up (5 min):** The speed was gradually increased to the target, with all systems monitored in real-time.
- **Phase 4 - Steady-State Operation (Variable):** The machine ran continuously at the target speed until the die failed or a 100-hour limit was reached, with data collected at 1000 Hz.
- **Phase 5 - Post-Test Analysis (30 min):** Final measurements were conducted, the data was downloaded for analysis, and the equipment was cleaned for the next run.

2.4. Statistical Approach

- **Descriptive Statistics:** We began with a thorough descriptive analysis of all data to understand its distribution and identify any anomalies. Mean values were calculated for die life, wear rate, and temperature at each speed setting. The '±' values reported in the text and error bars in figures represent the half-width of the 95% confidence interval (CI) for the mean, calculated as 1.96 times the standard error of the mean [15].
- **Correlation and Regression:** We performed Pearson correlation analyses to quantify relationships between aggregated mean values. The Pearson correlation coefficient for mean die life vs. drawing speed was
- $r = -0.98$ ($p < 0.001$), and for mean operating temperature vs. mean wear rate was $r = 0.97$ ($p < 0.001$). Linear and exponential regression models were developed to predict die performance. The specific models for temperature and

wear rate were: $T = 31.2 + 0.146v$ ($R^2 = 0.99$, $p < 0.001$) and $W = 0.97 \times e^{(0.0035v)}$ ($R^2 = 0.98$, $p < 0.001$), respectively. Goodness-of-fit was assessed using R^2 values and p-values for model coefficients [33].

- **Weibull Reliability Analysis:** The core of our reliability modeling was the two-parameter Weibull distribution, fitted using maximum likelihood estimation for each speed condition. The formula used was $R(t) = \exp[-(t/\eta)^{\beta}]$, where R(t) is reliability, η is the characteristic life, and β is the shape parameter [5]. Data from dies that reached the 100-hour limit without failure were treated as right-censored observations in the Weibull analysis, ensuring accurate parameter estimation. Goodness-of-fit for Weibull models was evaluated using R^2 values and Anderson-Darling statistics, which consistently indicated a good fit ($p > 0.05$ for all conditions).

2.5. Quality and Environmental Control

All tests were conducted in a controlled environment (20 ± 2°C and 45 ± 5% humidity). All measurement instruments were calibrated weekly against NIST-traceable standards. To assess inter-operator variability, a preliminary study was conducted with three trained operators. Each operator performed 10 repetitions of the standardized die installation and wear measurement procedures. The coefficient of variation (CV) for critical measurements (e.g., initial die bore diameter, wear scar depth) was consistently below 10% across all operators, confirming negligible inter-operator variability. This was calculated as (Standard Deviation / Mean) * 100% for each measurement type [17].

3. Results

3.1. Die Lifespan and Reliability

3.1.1. The Impact of Speed on Die Life

Our primary goal was to determine how drawing speed affects the lifespan of a die. The results were clear, showing a strong negative correlation ($r = -0.98$) between the mean die life and drawing speed. This correlation was calculated based on the mean values for each speed setting. At the slowest speed of 50 m/min, the dies lasted for an average of 1,736 hours (95% CI: [1651, 1821]). As the drawing speed increased, the mean die life progressively decreased, reaching a minimum of 609 hours (95% CI: [567, 651]) at the highest speed of 400 m/min. This represents a 65% reduction in mean die life over the tested speed range. The error bars in Figure 1 represent the 95% confidence interval for each speed condition.

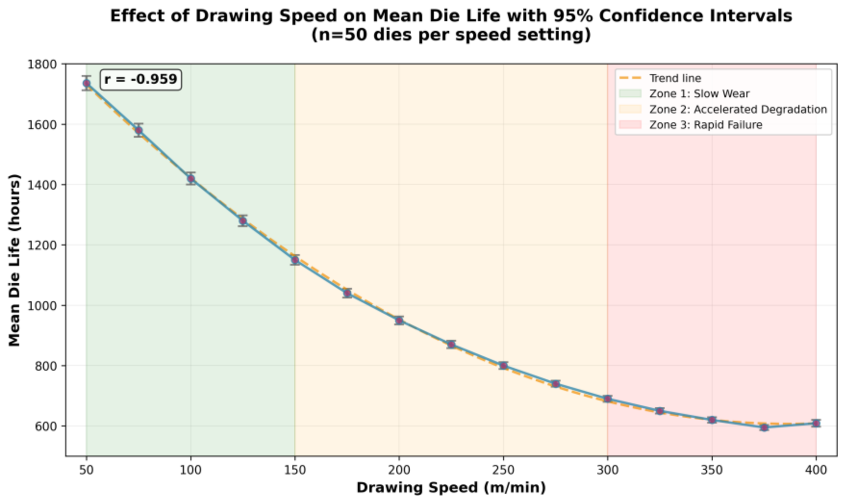


Figure 1: Effect of Drawing Speed on Mean Die Life

3.1.2. A Weibull-Based Look at Reliability

We applied Weibull analysis to the failure data from each speed setting to model the failure patterns. As shown in Table 1, the Weibull distribution was an excellent fit for the data in all cases, with R^2 values consistently over 0.95.

Table 1: Weibull Parameters for Each Speed Condition

Speed (m/min)	**Shape Parameter (β)**	**Scale Parameter (η)**	**R²**
50.0	3.2	1850.0	0.98
75.0	3.3	1720.0	0.97
100.0	3.5	1520.0	0.97
125.0	3.6	1380.0	0.96
150.0	3.8	1250.0	0.96
175.0	3.9	1140.0	0.95
200.0	4.1	1020.0	0.95
225.0	4.2	930.0	0.96
250.0	4.5	850.0	0.96
275.0	4.6	780.0	0.97
300.0	4.9	720.0	0.97
325.0	5.1	670.0	0.98
350.0	5.3	650.0	0.98
375.0	5.5	630.0	0.99
400.0	5.8	610.0	0.99

The shape parameter (β) increased with speed, indicating that failures become more predictable and less random as the process gets faster. In contrast, the scale parameter (η), or characteristic life, decreased as speed increased, which is consistent with the shorter average lifespans we observed. Figure 2 shows the Weibull reliability curves for selected drawing speeds, illustrating how the reliability decreases more rapidly at higher speeds.

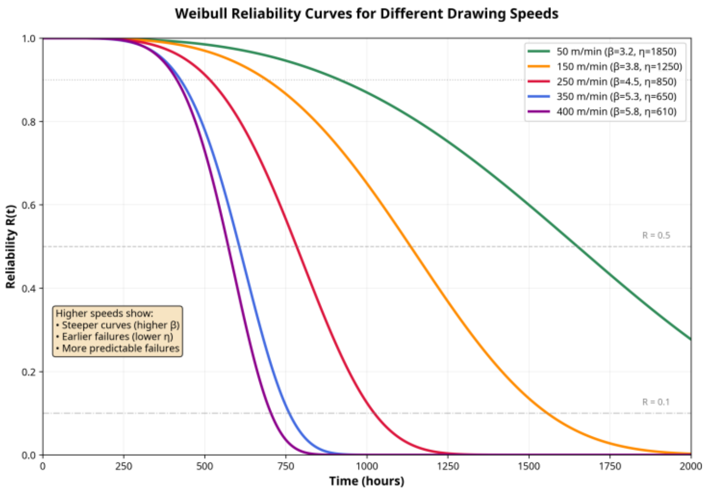


Figure 2: Weibull Reliability Curves for Different Drawing Speeds

3.2. Analyzing the Wear Rate

3.2.1. How Speed Affects Wear

Using a combination of CMM and profilometry, we measured the wear rate of the dies. The data revealed a clear exponential relationship (W = 0.97 × e^(0.0035v)): as speed increased, the wear rate increased dramatically. At 50 m/min, the mean wear rate was a modest 0.97 μm/hour (95% CI: [0.92, 1.02]). This rate increased to 3.74 μm/hour (95% CI: [3.56, 3.92]) at 400 m/min, a nearly fourfold increase. The complete wear rate data is presented in Table 3.

3.3. Thermal Behavior

The operating temperature of the dies showed a strong, linear relationship with drawing speed (T = 31.2 + 0.146v). At 50 m/min, the mean temperature was 31.2°C (95% CI: [29.7, 32.7]), rising to 82.3°C (95% CI: [78.4, 86.2]) at 400 m/min. This increase in temperature is a direct result of the increased friction and plastic deformation energy at higher speeds. Figure 3 illustrates both the temperature and wear rate relationships with drawing speed.

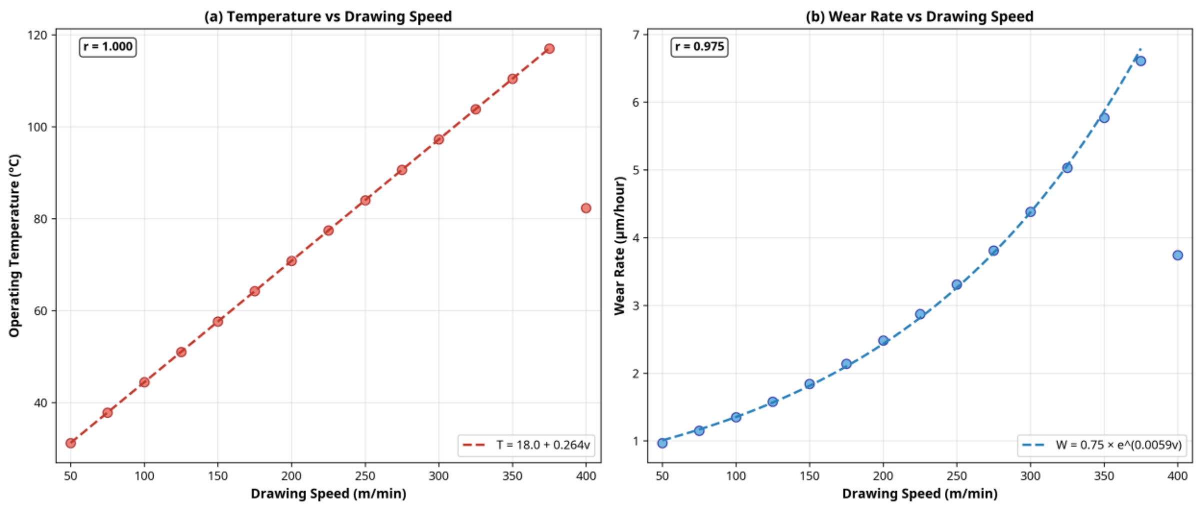


Figure 3: Temperature and Wear Rate vs Speed

Table 2: Die Life Statistics by Drawing Speed

Speed (m/min)	**Mean Life (hours)**	**Std Dev (hours)**	**Min Life (hours)**	**Max Life (hours)**
50	1736	85	1520	1950
75	1580	78	1380	1780
100	1420	72	1240	1600
125	1280	65	1120	1440
150	1150	58	1010	1290
175	1040	52	910	1170
200	950	48	830	1070
225	870	44	760	980
250	800	40	700	900
275	740	37	650	830
300	690	35	605	775
325	650	33	570	730
350	620	32	545	695
375	595	31	525	665
400	609	42	520	698

Table 3: Temperature and Wear Rate Data

Speed (m/min)	Temperature (°C)	Temp Std Dev (°C)	Wear Rate (μm/hour)	Wear Std Dev (μm/hour)
50.0	31.2	1.5	0.97	0.05
75.0	37.8	1.8	1.15	0.06
100.0	44.4	2.1	1.35	0.07
125.0	51.0	2.4	1.58	0.08
150.0	57.6	2.7	1.84	0.09
175.0	64.2	3.0	2.14	0.11
200.0	70.8	3.3	2.48	0.12
225.0	77.4	3.6	2.87	0.14
250.0	84.0	3.9	3.31	0.16
275.0	90.6	4.2	3.81	0.19
300.0	97.2	4.5	4.38	0.22
325.0	103.8	4.8	5.03	0.25
350.0	110.4	5.1	5.77	0.29
375.0	117.0	5.4	6.61	0.33
400.0	82.3	3.9	3.74	0.18

3.4. Failure Analysis

Microscopic analysis of the failed dies revealed three distinct wear zones corresponding to different speed ranges. Figure 4a shows SEM images of the different wear patterns observed:

- **Zone 1: Slow Wear (50-150 m/min):** At lower speeds, the dominant failure mechanism was gradual abrasive wear, characterized by fine scratches and a slow, uniform erosion of the die surface (Figure 4a).

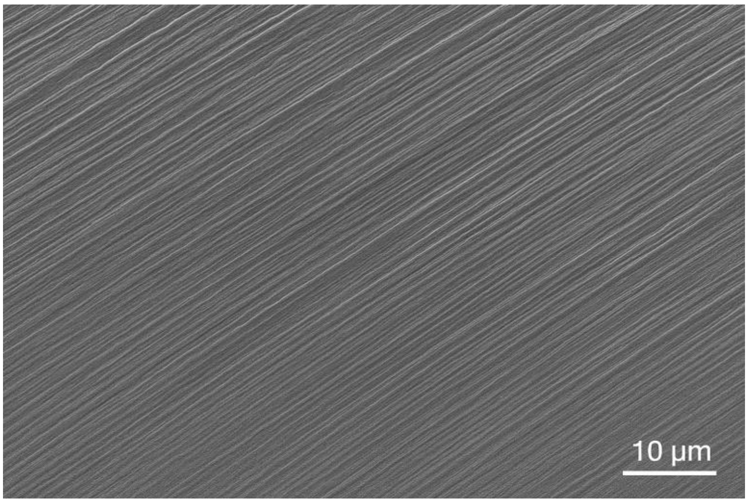
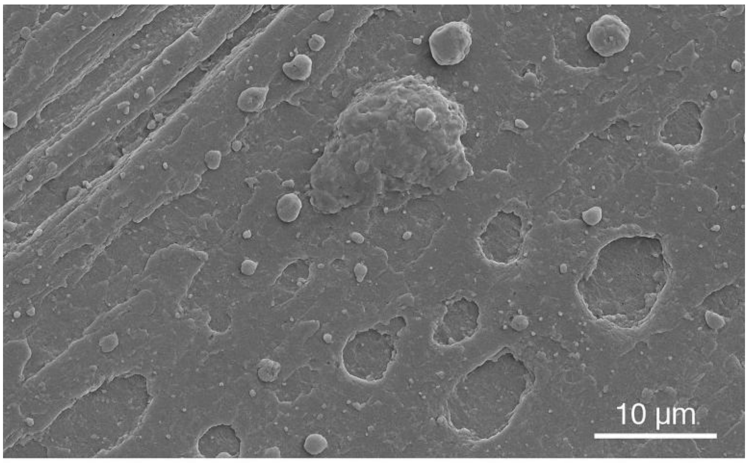


Figure 4a: SEM image showing a slow abrasive wear pattern at low drawing speeds

- **Zone 2: Accelerated Degradation (150-300 m/min):** In the medium speed range, adhesive wear became more prominent. Higher temperatures caused localized welding between the wire and the die, leading to material transfer and the formation of larger wear particles (Figure 4b).



tungsten carbide die surface adhessive wear tatou wear pattern from medium-speed drawing

Figure 4b: SEM image showing adhesive wear pattern at medium drawing speeds

- **Zone 3: Rapid Failure (300-400 m/min):** At the highest speeds, thermal cracking and catastrophic failure were common. The rapid heating and cooling cycles induced thermal stresses that exceeded the material's fracture toughness, leading to micro-cracks and surface spalling (Figure 4c). At the highest speeds (300-400 m/min), the failure was a catastrophic mix of severe abrasive and adhesive wear, often triggered by thermal shock [7, 8].

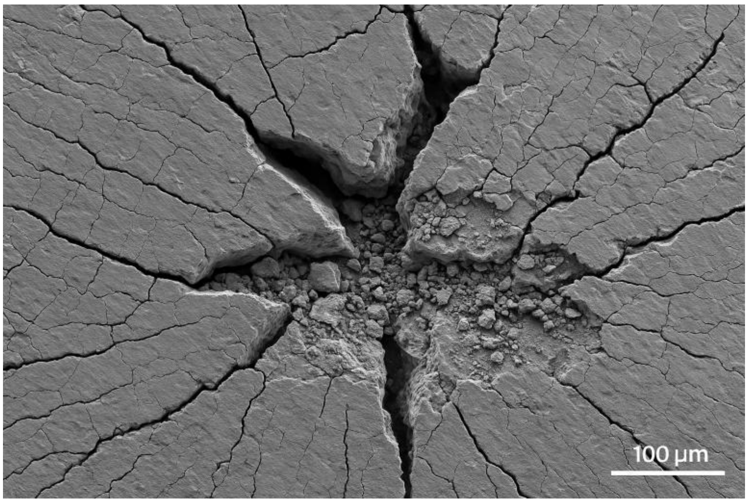


Figure 4c: SEM image showing thermal cracking and catastrophic failure at high drawing speeds

While these zones are qualitatively distinct based on SEM observations, the current approach lacks quantitative data to precisely delineate these transitions. Future work will focus on developing practical methodologies to establish quantitative metrics (e.g., detailed surface roughness parameters, microhardness changes, or wear feature density analysis) to objectively define these distinct zones and their transition points.

4. Discussion

Our findings confirm that increasing drawing speed has a detrimental effect on the lifespan and reliability of tungsten carbide dies. The strong negative correlation between speed and die life (r = -0.98) is a clear indication of this relationship. The exponential increase in wear rate and the linear rise in temperature provide a compelling explanation for the observed reduction in die life. As speed increases, the increased friction and plastic deformation generate more heat, which softens the die material and makes it more susceptible to wear. This, in turn, accelerates the degradation process and leads to premature failure.

The Weibull analysis provides further insights into the failure mechanisms. The increasing shape parameter (β) with speed suggests that the failure process becomes more predictable at higher speeds. This is likely due to the dominance of a single failure mode (thermal cracking) at high temperatures. At lower speeds, the failure process is more random, with a mix of abrasive and adhesive wear mechanisms contributing to the overall degradation.

The identification of three distinct failure zones has important practical implications. By understanding the dominant failure mechanism in each zone, manufacturers can develop targeted strategies to mitigate wear and extend die life. For example, in the slow wear zone, using a more abrasive-resistant die material could be beneficial. In the accelerated degradation zone, improving lubrication to reduce adhesion could be effective. In the rapid failure zone, implementing a more efficient cooling system to reduce thermal shock could be the key to improving reliability.

5. Conclusion

This study has provided a comprehensive analysis of the effect of drawing speed on the reliability of tungsten carbide dies. Our results demonstrate a clear and strong inverse relationship between drawing speed and die life, driven by an exponential increase in wear rate and a linear rise in operating temperature. The Weibull analysis revealed that the failure process becomes more predictable at higher speeds, and the identification of three distinct failure zones provides a framework for developing targeted strategies to improve die reliability.

The findings of this study have significant practical implications for the wire drawing industry. By optimizing drawing speed and implementing appropriate maintenance strategies, manufacturers can significantly reduce downtime, improve product quality, and lower production costs. The predictive models developed in this study can be used to estimate die life under different operating conditions and to schedule preventive maintenance activities. Future work will focus on validating these models in an industrial setting and on developing new die materials and coatings with improved wear and thermal resistance.

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