

PART 1 – Single Dataset Engineering Tasks

Task 4: Hardness Scale Correlation

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Abstract

This report presents a comprehensive analysis of hardness scale correlation in engineering materials, focusing on Task 4 of the materials dataset. We examine the relationships between Brinell (Bhn) and Vickers (HV) hardness scales and their correlations with other mechanical properties such as tensile strength, yield strength, and ductility. The analysis reveals significant patterns in material performance and provides crucial insights for material selection in engineering applications. Data quality observations highlight important considerations for interpreting hardness measurements and their implications for predicting material behavior.

1 Introduction

Hardness Measurement in Materials Science

Hardness testing provides a vital method for assessing material properties through relatively simple, non-destructive means. This report analyzes the relationships between different hardness scales (Brinell and Vickers) and investigates how these measurements correlate with other mechanical properties. Understanding these correlations is fundamental for engineering applications where direct tensile or yield strength testing may be impractical, allowing hardness to serve as a reliable proxy for estimating other material characteristics. Through statistical analysis of correlation strengths and patterns, this report illuminates how hardness measurements can guide material selection decisions while highlighting the limitations and considerations necessary for proper interpretation of hardness data.

2 Data Quality Observations

The analysis of hardness scales reveals critical data quality issues that affect the reliability and comprehensiveness of the hardness correlation analysis.

Missing Data Patterns

A critical observation from Task 4 is the complete absence of samples with both Brinell and Vickers hardness values simultaneously present. The analysis reveals:

- 463 samples with Brinell hardness values
- 165 samples with Vickers hardness values
- 0 samples with both values present

This significant data quality issue prevents direct correlation between the two hardness scales, forcing the analysis to rely on indirect correlations through other mechanical properties. This limitation could introduce uncertainty in material selection decisions that depend on comparing materials tested with different hardness methods.

Correlation Strength Variability

The analysis shows that correlation strengths vary between properties and testing methods:

- Brinell hardness shows stronger linear correlations with strength metrics (Pearson correlation > 0.86)
- Vickers hardness shows moderate linear correlations with strength (0.55-0.62)
- The ductility correlation is better captured by Spearman (rank-based) than Pearson (linear) analysis

This variability in correlation quality suggests that material selection based on hardness should account for the specific type of hardness test performed and the relationship pattern involved.

3 Brinell Hardness Correlation Analysis

Brinell hardness (Bhn) demonstrates strong correlations with mechanical properties, particularly strength characteristics, making it a valuable predictor for material performance.

Table 1: Pearson Correlation Coefficients for Brinell Hardness

Relationship	Correlation Coefficient	Interpretation
Bhn vs Su	0.900	Very strong positive linear relationship
Bhn vs Sy	0.866	Strong positive linear relationship
Bhn vs A5	-0.109	Weak negative linear relationship

Brinell Hardness Relationship Insights

The analysis of Brinell hardness correlations reveals several key patterns with important engineering implications:

- **Strength-Hardness Relationship:** The remarkably high Pearson correlation between Brinell hardness (Bhn) and ultimate tensile strength (Su) at 0.900 confirms that hardness testing can serve as a reliable proxy for strength estimation when direct tensile testing is impractical.
- **Yield Strength Prediction:** With a similarly strong correlation to yield strength (Sy) at 0.866, Brinell hardness provides effective prediction of material yield behavior, critical for designing against plastic deformation.
- **Ductility Correlation:** The weak Pearson correlation between Bhn and elongation (A5) at -0.109 suggests a limited linear relationship between hardness and ductility when using Brinell measurements, although the expected inverse relationship is still visible.
- **Application Guidance:** For material selection purposes, engineers can confidently use Brinell hardness testing as a quick, non-destructive screening method to identify candidates meeting strength requirements, particularly for load-bearing applications like structural components, transmission elements, or fasteners.

4 Vickers Hardness Correlation Analysis

Vickers hardness (HV) shows different correlation patterns compared to Brinell, particularly in its relationship with ductility, highlighting the importance of test method selection.

Table 2: Spearman Correlation Coefficients for Vickers Hardness

Relationship	Correlation Coefficient	Interpretation
HV vs Su	0.559	Moderate-to-strong monotonic increase
HV vs Sy	0.617	Moderate-to-strong monotonic increase
HV vs A5	-0.461	Moderate monotonic decrease

Vickers Hardness Relationship Insights

The Spearman correlation analysis of Vickers hardness reveals important patterns distinct from Brinell measurements:

- **Strength Correlation:** Vickers hardness shows moderate-to-strong monotonic relationships with ultimate tensile strength (0.559) and yield strength (0.617), confirming HV as a reliable predictor of strength properties, though less linear than Brinell.
- **Hardness-Ductility Trade-off:** The Spearman correlation between HV and elongation (A5) shows a much stronger negative relationship of -0.461, indicating a meaningful monotonic decrease in ductility as hardness increases, better capturing this critical material science principle.
- **Non-Linear Relationships:** The significant difference between Pearson and Spearman correlations suggests that relationships between hardness and other properties, particularly ductility, follow non-linear patterns that are better captured by rank-based correlation analysis.
- **Application Implications:** Materials with Vickers hardness exceeding HV 500 typically show significant ductility reduction, a crucial consideration for applications requiring deformability such as sheet metal forming, energy-absorbing crash structures, or components subject to impact or vibration.

5 Hardness Testing Method Significance

Different hardness testing methods (Brinell vs. Vickers) yield different results and correlations, with important implications for material selection and property prediction.

Table 3: Comparison of Brinell and Vickers Hardness Testing Characteristics

Characteristic	Brinell Hardness (Bhn)	Vickers Hardness (HV)
Indenter Type	10mm steel/carbide ball	Diamond pyramid
Test Load	Typically 3000 kgf	1-50 kgf (micro to macro)
Measurement Scale	Wider range for softer materials	Applicable to very hard materials
Surface vs. Bulk	Measures bulk properties	Better for surface and local properties
Correlation with Su	Strong linear (0.900)	Moderate monotonic (0.559)
Correlation with A5	Weak linear (-0.109)	Moderate monotonic (-0.461)

Surface vs. Bulk Properties

The difference between hardness measurement techniques reveals the importance of matching the test method to the application requirements:

- **Vickers Testing Advantages:** With smaller indenter and lighter loads, Vickers better captures surface and local hardness variations, making it more appropriate for:
 - Surface-critical applications (wear surfaces, contact interfaces)
 - Thin components or coatings
 - Materials with heterogeneous microstructures
- **Brinell Testing Advantages:** With its larger indenter and heavier test load, Brinell provides better bulk property evaluation, making it more suitable for:
 - Heavy structural components
 - Cast components that may have internal variations
 - Applications where average properties are more relevant than local extremes
- **Material-Specific Considerations:** The data suggests that hardness correlation patterns may vary significantly by material family, requiring engineers to:
 - Use standardized hardness-strength conversion factors specific to each material family
 - Understand which hardness test is historically better correlated for specific materials (e.g., Brinell for cast irons, Vickers for hardened steels)
 - Consider additional testing when materials fall outside typical correlation patterns

6 Potential Causes of Hardness Scale Divergence

Understanding why Brinell and Vickers hardness measurements might diverge for the same material provides critical insight for proper test selection and result interpretation.

Table 4: Potential Causes of Discrepancy Between Hardness Scales

Possible Reason	Explanation	Example Cases
Surface Treatment	HV's small indenter better detects surface hardening layers	Case-hardened gears, carburized shafts
Indentation Size Effect	HV's micro-load measures local properties; Bhn averages bulk	Thin coatings, small components
Material Heterogeneity	HV reveals microstructural variations; Bhn blends them	Dual-phase steels, castings with pores
Testing Standards	Calibration errors, operator technique, protocol differences	Non-standardized labs, worn indenters
Scale Conversion Limits	Empirical conversion formulas fail for certain materials	Titanium alloys, tool steels

Key Insights on Scale Divergence

The analysis suggests that HV and Bhn correlate well for homogeneous bulk materials but diverge most significantly when:

- **Surface Treatments Alter Local Hardness:** Case-hardened or surface-treated components will show higher Vickers hardness values near the surface while Brinell tests may penetrate beyond the treated layer, yielding lower values that reflect more of the base material.
- **Microstructure Varies at Small Scales:** Materials with non-uniform microstructures (e.g., dual-phase steels, precipitation-hardened alloys) will show more variation in Vickers measurements due to the smaller indentation area, while Brinell provides an averaged result.
- **Materials Defy Standard Conversion Trends:** Empirical conversion formulas between hardness scales are typically derived from carbon steels and may not apply accurately to specialty alloys, particularly non-ferrous metals, leading to systematic errors when converting between scales.
- **Testing Protocol Inconsistencies:** Variations in sample preparation, testing conditions, or equipment calibration can introduce systematic differences

between testing methods, particularly when measurements are performed in different laboratories or time periods.

7 Material Selection Based on Hardness Analysis

Hardness correlations provide valuable guidance for material selection across different engineering applications, with specific insights for optimizing material choices.

Table 5: Material Selection Guidelines Based on Hardness Correlations

Application Focus	Recommended Approach	Hardness Consideration
Strength-critical components	Use Bhn as primary screening metric	High correlation (0.900) ensures reliable strength prediction
Wear-resistant surfaces	Focus on local HV measurements	Surface hardness better captures wear resistance potential
Energy-absorbing structures	Moderate HV (200-400)	Maintains balance between strength and ductility
Fasteners and connections	High Bhn with adequate A5	Ensures strength while preventing brittle failure
Sheet metal forming	Lower Bhn, higher A5	Optimizes formability while maintaining adequate strength

Application-Specific Guidelines

The hardness correlation analysis supports these material selection strategies for engineers:

- Structural Components:** For load-bearing applications like structural beams, columns, and chassis components, Brinell hardness serves as an excellent screening tool due to its high correlation with tensile and yield strength. Materials with Bhn 150-300 typically provide optimal balance of strength and fabricability.
- Wear-Critical Applications:** For components subject to abrasion, erosion, or contact wear, Vickers hardness better predicts performance due to its sensitivity to surface properties. Target HV values above 500 for severe wear conditions, but remain cognizant of the corresponding reduction in ductility.
- Impact-Resistant Components:** For parts subject to impact loading, balance moderate hardness with adequate ductility. The Spearman correlation between HV and A5 (-0.461) suggests that hardness values should be kept below HV 400 when impact resistance is critical.
- Precision Components:** For parts requiring dimensional stability and minimal distortion, use Brinell hardness to predict strength while ensuring adequate

yield strength (via the 0.866 correlation) to prevent plastic deformation under service loads.

- **Fatigue-Critical Applications:** For cyclically loaded components, moderate hardness values that balance strength with sufficient ductility typically provide optimal fatigue resistance. The correlation analyses suggest targeting materials with moderate Bhn (150-250) that retain elongation values above 10

8 Recommendations for Improved Data Collection

To enhance material selection confidence based on hardness data, several improvements to data collection practices are recommended.

Data Quality Enhancement Strategies

To improve the reliability and utility of hardness data for material selection decisions:

- **Standardized Testing Protocols:** Implement standardized testing protocols that collect both Brinell and Vickers measurements on the same specimens, enabling direct correlation between scales and validation of conversion factors.
- **Comprehensive Hardness Measurement:** Include additional hardness measurements (e.g., Rockwell scales) to enable comprehensive cross-scale validation and provide multiple reference points for property estimation.
- **Documentation Enhancement:** Document specific testing conditions and equipment calibration details to improve test reproducibility and enable identification of systematic measurement variations.
- **Material Classification:** Separate surface-treated materials from bulk-uniform materials in the database to avoid confounding factors when analyzing hardness-property relationships.
- **Uncertainty Quantification:** Track measurement uncertainty ranges alongside reported values to improve confidence in correlation analysis and provide bounds for property estimation.
- **Material-Specific Correlation Models:** Develop separate correlation models for different material families rather than applying single conversion factors across all materials.

By addressing these data quality concerns, future material selection processes could more reliably utilize hardness measurements as screening criteria for engineering applications.

9 Conclusions

The hardness scale correlation analysis provides valuable insights for engineering material selection while highlighting important data quality considerations.

Key Takeaways

The analysis of hardness scale correlations reveals several crucial insights for engineering applications:

- **Strength-Hardness Relationship:** Both Brinell and Vickers hardness measurements demonstrate strong positive correlations with tensile and yield strength, confirming that hardness testing can serve as a reliable proxy for strength estimation when direct tensile testing is impractical.
- **Hardness-Ductility Trade-off:** While Brinell hardness shows only a weak linear correlation with elongation, Vickers hardness demonstrates a stronger negative monotonic relationship with ductility, better capturing the inverse relationship between hardness and deformability.
- **Test Method Significance:** Different hardness testing methods (Brinell vs. Vickers) yield different results and correlations, particularly for certain material classes, highlighting the importance of matching the test method to the application requirements.
- **Data Quality Impact:** The complete absence of samples with both Brinell and Vickers hardness values simultaneously present represents a significant limitation that prevents direct correlation between the scales and necessitates reliance on indirect correlations through other properties.
- **Material Selection Guidance:** Hardness measurements provide an efficient first-pass evaluation method for material selection, particularly for load-bearing applications, wear-resistant components, and parts requiring specific combinations of strength and ductility.

Engineers should consider the specific type of hardness test performed, the material family involved, and potential non-linear relationships when using hardness data to guide material selection decisions. Improvements in data collection practices would significantly enhance the reliability and utility of hardness measurements for engineering applications.

Plot Analysis of HV (Brinell Hardness) vs. Su, Sy, A5

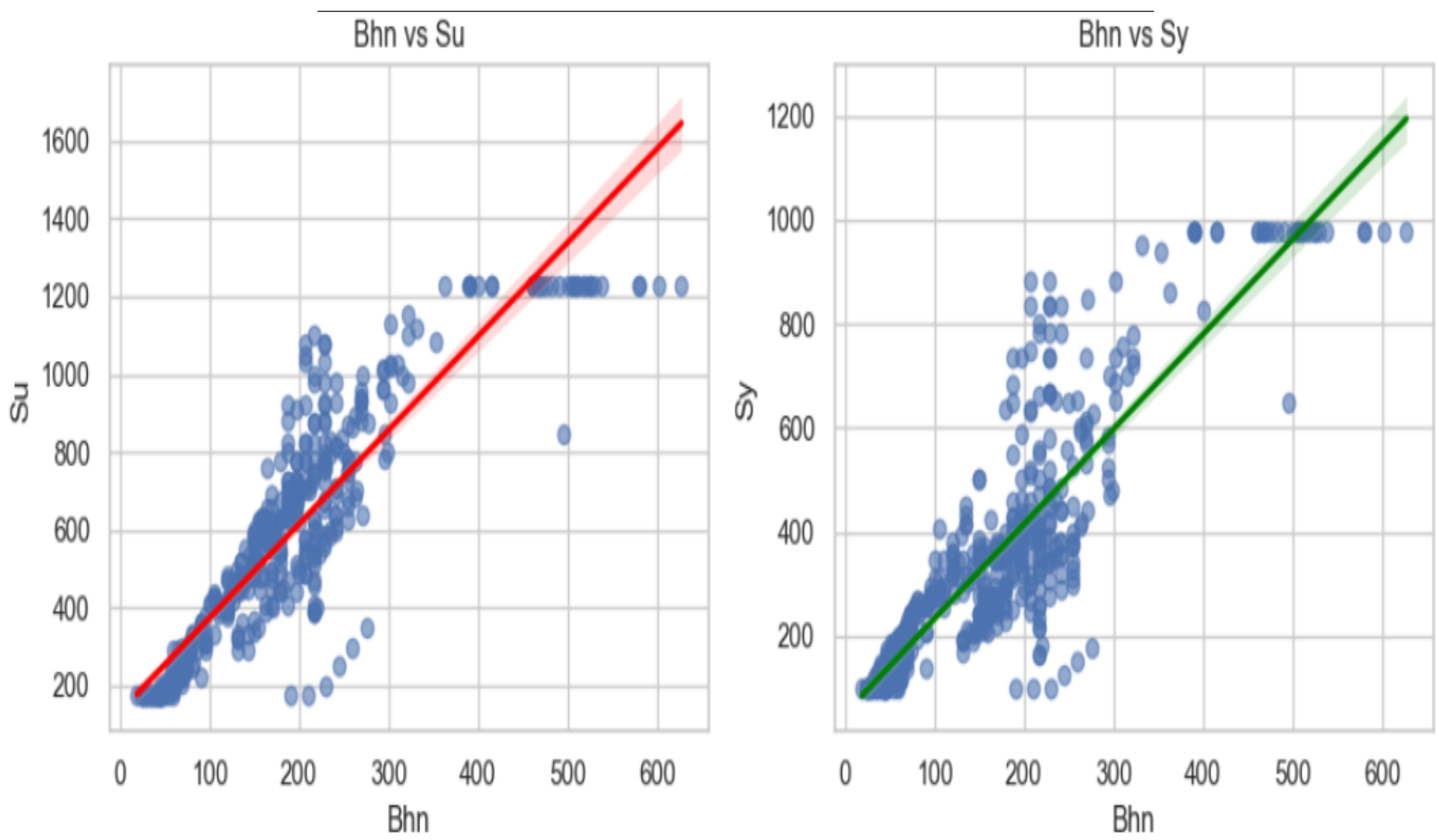


Figure 1: Brinell Hardness vs. Ultimate (Su) and Yield Strength (Sy). Trend lines: Su - Red, Sy - Green.

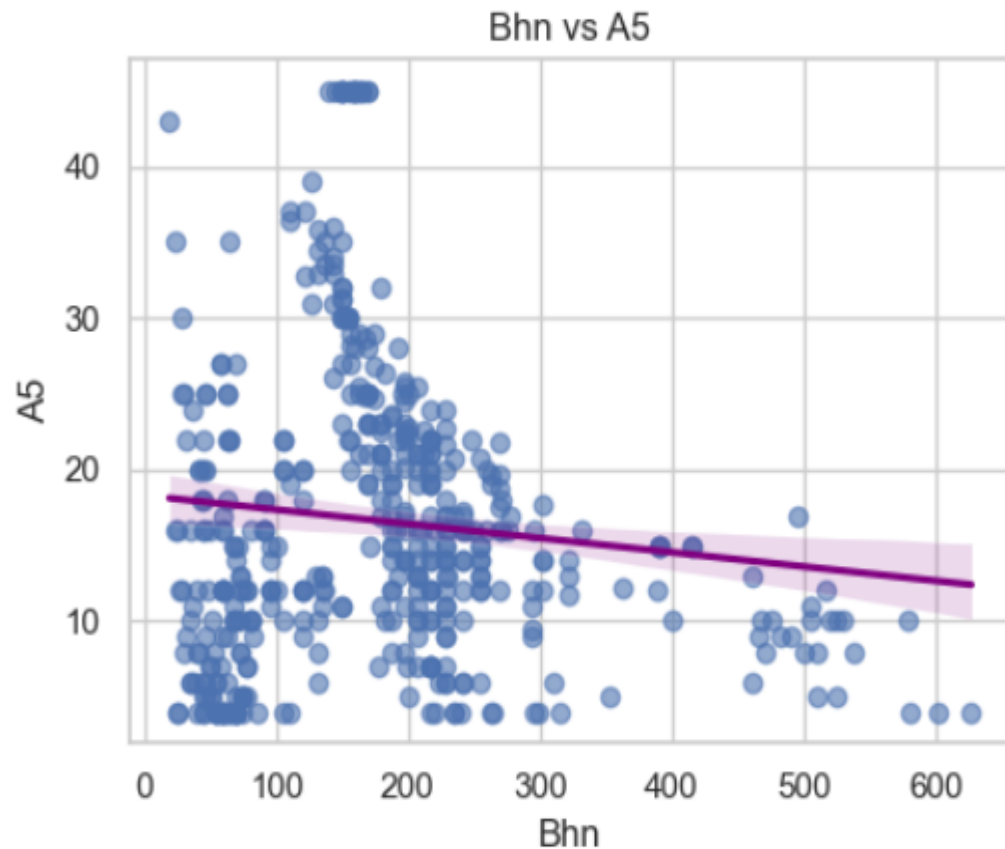


Figure 2: Brinell Hardness vs. Ductility (A5). Trend line: Purple (Negative Correlation).

Observations and Interpretation

- **Bhn vs Su & Sy (Strength):**
 - As Brinell Hardness (Bhn) increases, both **Ultimate Tensile Strength (Su)** and **Yield Strength (Sy)** increase.
 - Clear positive trend lines — red for Su, green for Sy.
 -  **Implication:** Harder materials tend to be stronger in both tensile and yield behavior.
- **Bhn vs A5 (Ductility):**
 - As Bhn increases, **Elongation at Break (A5)** decreases.
 - A negative purple trend line indicates reduced ductility with increased hardness.
 -  **Trade-off:** Higher hardness compromises ductility, increasing the risk of brittle failure.

Summary of Correlation Trends:

Relationship	Correlation	Trend Color	Line	Implication
Bhn → Su (Tensile Strength)	Positive	Red		Harder = Stronger (tensile)
Bhn → Sy (Yield Strength)	Positive	Green		Harder = Stronger (yield)
Bhn → A5 (Ductility)	Negative	Purple		Harder = Less Ductile

Table 6: Summary of Hardness-Based Correlations

Engineering Takeaways:

- **Strength-Hardness Synergy:** Increasing hardness boosts strength, ideal for structural or load-bearing parts.
- **Ductility Trade-off:** Watch for reduced flexibility — harder materials are more brittle.
- **Design Tip:** Balance hardness with formability depending on whether you prioritize strength or ductility.

Plot Analysis of HV (Vickers Hardness) vs. Su, Sy, A5

1. HV vs. Ultimate Tensile Strength (Su)
Trend: As HV increases (100 → 800), Su shows a strong positive correlation, rising from ~200 MPa to ~1400 MPa. Data points cluster tightly around the (implied) trend line.
Insight: Higher Vickers Hardness correlates with increased tensile strength — typical for hardened steels/alloys that restrict dislocation motion.

2. HV vs. Yield Strength (Sy)
Trend: Similar positive trend; Sy increases with HV, but remains below Su (e.g., 150–1200 MPa).
Insight: Improved hardness boosts yield strength — crucial to prevent permanent deformation.

3. HV vs. Ductility (A5)
Trend: A5 drops sharply (25% → 5%) as HV rises.
Insight: Classic strength-ductility trade-off — ultra-hard materials (HV > 500) become brittle and unsuitable for elongation-critical use.

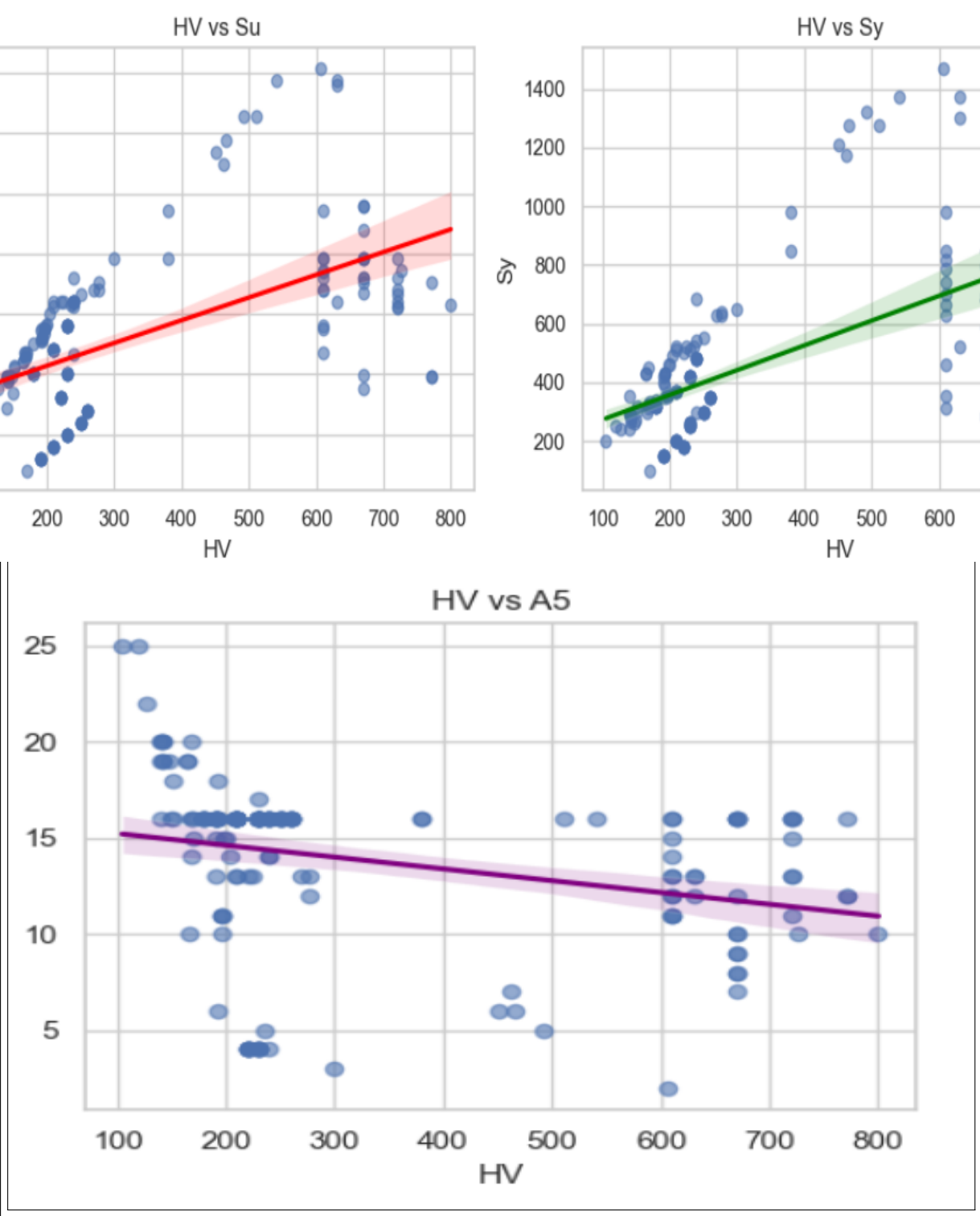


Figure 3: Relationships between Vickers Hardness (HV) and Su, Sy, A5

Table 7: Summary of HV Relationships and Engineering Implications

Relationship	Correlation	HV Range	Engineering Implication
HV → Su	Strong +	200–800	Higher hardness = Higher load-bearing capacity
HV → Sy	Strong +	200–800	Better resistance to plastic deformation
HV → A5	Strong –	200–800	Harder materials risk brittle failure

Key Takeaways

- **HV 200–400:** Best for ductile applications (e.g., automotive bodies).
- **HV 500–800:** Excellent for wear-resistance (e.g., gears, tools) — but check fracture toughness.
- **Design Trade-off:** Maximizing hardness reduces ductility — choose based on application needs.
- **Validate:** Compare results with datasheets (e.g., SAE 4340 at HV 400 vs. 600).