

# PART 1 – Single Dataset Engineering Tasks

## Task 3: Design Ratio Analysis

April 30, 2025

### Abstract

This report presents a specialized analysis of engineering materials based on Task 3 (Design Ratio Analysis) of the materials dataset. We examine three critical custom strength metrics: Strength-to-Hardness ratio, Strength-to-Ductility index, and Strength-to-Weight proxy, revealing significant patterns in material performance profiles. The analysis provides essential insights for engineering material selection based on application-specific requirements, highlighting the intrinsic trade-offs between different performance metrics. Material-specific recommendations are provided alongside data quality observations to support informed engineering decisions.

## 1 Introduction

### Custom Metrics for Enhanced Material Selection

Engineering materials selection often requires consideration of multiple properties simultaneously rather than focusing on individual metrics. This report analyzes the dataset using custom ratio metrics designed to highlight specific performance attributes of materials: Strength-to-Hardness ( $S_u/B_{hn}$ ), Strength-to-Ductility ( $S_u \times A_5$ ), and Strength-to-Weight ( $S_u/R_o$ ). By examining how materials perform across these ratios, engineers can identify optimal candidates for specific applications and understand the inherent trade-offs involved in material selection decisions. This analysis provides data-driven guidance for critical engineering choices where particular combinations of properties determine performance success.

## 2 Material Selection Insights

### 2.1 Strength-to-Hardness Ratio Analysis

The Strength-to-Hardness ratio ( $S_u/B_{hn}$ ) reveals materials that offer excellent strength relative to their hardness, which is particularly valuable for applications requiring both strength and machinability or formability.

Table 1: Top Materials by Strength-to-Hardness Ratio

Material	Heat Treat-ment	Strength-to-Hardness	Application Suit-ability
Aluminum Alloy 1060-O	Wrought	9.42	Forming operations, low-stress applications
Aluminum Alloy 1060-H12	Wrought	7.78	Slightly stronger, still highly formable
Aluminum Alloy 1100-O	Wrought	7.78	General forming, good corrosion resistance
Aluminum Alloy B443.0	Cast (F)	7.16	Cast components with good machinability
Aluminum Alloy 6063-O	Wrought	7.16	Architectural ex-trusions, detail components

Strength-to-Hardness Insights

The analysis of Strength-to-Hardness ratios reveals several key patterns with important engineering implications:

- **Aluminum Dominance:** Wrought aluminum alloys significantly outperform other materials in this metric, with values reaching 9.42 for Aluminum Alloy 1060-O.
- **Heat Treatment Impact:** The annealed (O) condition consistently produces higher Strength-to-Hardness ratios compared to hardened states, highlighting the impact of processing on this property relationship.
- **Cast vs. Wrought Comparison:** While wrought alloys lead this metric, cast aluminum B443.0 still performs exceptionally well (7.16), indicating good machinability potential in properly selected cast alloys.
- **Application Guidance:** Materials with high Su/Bhn ratios are ideal candidates for applications requiring secondary machining operations, moderate strength components with complex geometry, or parts requiring excellent formability and moderate strength.

2.2 Strength-to-Ductility Index Analysis

The Strength-to-Ductility index ( $S_u \times A_5$ ) identifies materials that provide an optimal balance of strength and ability to deform before fracture, crucial for applications requiring toughness and energy absorption.

Table 2: Top Materials by Strength-to-Ductility Index

Material	Heat Treatment	Strength-to-Ductility	Application	Suit-
Steel SAE 30301	Annealed	34,110	High-impact resistance, fatigue applications	re-
Steel SAE 30314	Annealed	31,005	Extreme toughness requirements	
Steel SAE 30302B	Annealed	29,475	Biomedical, corrosion + toughness needs	
Steel SAE 30310	Annealed	29,475	High-temperature tough applications	
Steel SAE 30347	Annealed	28,530	Stabilized grade for welded structures	

Strength-to-Ductility Insights

The Strength-to-Ductility index analysis reveals critical patterns for engineering applications requiring balanced mechanical performance:

- **Stainless Steel Superiority:** The SAE 303 series stainless steels in annealed condition dominate this category with exceptionally high values reaching 34,110 for SAE 30301.
- **Heat Treatment Consistency:** The annealed condition consistently produces superior Strength-to-Ductility performance across all top performers, indicating this heat treatment’s critical role in optimizing toughness.
- **Material Family Pattern:** The overwhelming dominance of austenitic stainless steels suggests their microstructural characteristics intrinsically support excellent strength-ductility combinations.
- **Application Implications:** These materials are ideal candidates for critical safety components, energy-absorbing structures, and applications subject to impact loading or requiring significant deformation before failure.

2.3 Strength-to-Weight Ratio Analysis

The Strength-to-Weight ratio ( $S_u/R_o$ ) highlights materials offering maximum strength for their weight, crucial for weight-critical applications in aerospace, automotive, and portable equipment design.

Table 3: Top Materials by Strength-to-Weight Ratio

Material	Heat Treatment	Strength-to-Weight	Application Suitability
Aluminum Alloy 7075-T6	Wrought	0.212	Aerospace structural components
Aluminum Alloy 7075-T651	Wrought	0.212	Stress-relieved aerospace structures
Aluminum Alloy 7049-T73	Wrought	0.191	Corrosion-resistant aerospace parts
Aluminum Alloy 7049-T7352	Wrought	0.191	Stress-relieved aircraft components
Aluminum Alloy 2024-T361	Wrought	0.184	Aircraft fuselage, structural frames

Strength-to-Weight Insights

The analysis of Strength-to-Weight ratios yields important insights for weight-critical engineering applications:

- **7000-Series Excellence:** Aluminum alloys in the 7000 series (particularly 7075-T6/T651) demonstrate superior performance with values reaching 0.212, significantly outperforming other material families.
- **Heat Treatment Criticality:** The T6 and T73 tempers consistently produce superior Strength-to-Weight ratios compared to other conditions, highlighting the importance of precipitation hardening treatments.
- **Consistency Pattern:** The remarkably consistent Strength-to-Weight values (approximately 0.2) among top performers suggests these materials have been specifically engineered and optimized for weight-efficient structural applications.
- **Application Targeting:** These materials represent optimal choices for aerospace components, high-performance sporting equipment, portable devices, and automotive components where weight reduction directly impacts energy efficiency or performance.

3 Material Selection Trade-offs

The multi-ratio analysis reveals critical trade-offs that engineers must consider when selecting materials for specific applications.

Table 4: Material Performance Trade-offs Across Multiple Ratios

Material	Strength-to-Hardness	Strength-to-Ductility	Strength-to-Weight	Trade-off Pattern
7075-T6	Low	High	High	Sacrifices machinability for strength efficiency
7049-T73	Low-Moderate	Low-Moderate	High	Balanced compromise across metrics
7049-T7352	Very Low	Very Low	High	Extreme optimization of weight at expense of other properties
1060-O	Very High	Low	Low	Optimized for forming at expense of strength
SAE 30301	Moderate	Very High	Low	Maximizes toughness at expense of weight efficiency

Key Trade-off Insights

The cross-ratio analysis reveals fundamental material selection trade-offs with significant engineering implications:

- **Property Exclusivity:** The data clearly demonstrates that simultaneous optimization of all three ratios is impossible with existing materials—excellence in one metric typically comes at the expense of another.
- **Heat Treatment Impact:** The same base material treated differently (e.g., 7049-T73 vs. 7049-T7352) shows dramatically different ratio profiles, emphasizing processing as a key lever for property customization.
- **Material Family Specialization:** Different material families show distinct ratio strengths—aluminum alloys excel in Strength-to-Weight and Strength-to-Hardness, while stainless steels dominate Strength-to-Ductility performance.
- **Application Prioritization:** Material selection must be driven by which property ratio is most critical for a specific application, with clear understanding of the compromises being accepted in other performance areas.

4 Material Selection Guidelines

Based on the custom ratio analysis, specific material selection recommendations can be made for common engineering applications.

Table 5: Recommended Materials by Application Requirements

Application Requirement	Re-	Recommended Material	Key Ratio	Strength	Accepted Trade-offs
Lightweight structures		Aluminum Alloy 7075-T6/T651		Strength-to-Weight (0.212)	Lower machinability
Energy absorption		Steel SAE 30301 (annealed)		Strength-to-Ductility (34,110)	Higher weight
Complex machined components		Aluminum Alloy 1060-O		Strength-to-Hardness (9.42)	Lower absolute strength
Balanced performance		Aluminum Alloy 7049-T73		Moderate in all ratios	No exceptional properties
Corrosion-resistant structures		Steel SAE 30310/30347	High	Strength-to-Ductility	Lower weight efficiency

### Material Selection Strategy

The ratio analysis supports these material selection strategies for engineers:

- **Application-Driven Selection:** Begin material selection by identifying which ratio is most critical for your specific application requirements.
- **Balanced Consideration:** When multiple properties matter, consider materials like 7049-T73 that offer moderate performance across multiple ratios rather than excellence in just one.
- **Processing Optimization:** Consider how heat treatment can be used to shift the balance of properties toward your specific performance requirements.
- **Specialty Applications:** For extreme performance requirements, select materials that specifically excel in the critical ratio, accepting the inevitable compromises in other areas.
- **Industry-Specific Guidance:** For aerospace and transportation, prioritize 7000-series aluminum alloys; for energy-absorbing and safety-critical components, consider annealed 300-series stainless steels; for complex machined components with moderate strength needs, select 1000-series aluminum in O-condition.

## 5 Data Quality Observations

## Data Quality Considerations

Several data quality issues affect the reliability and comprehensiveness of the custom ratio analysis:

- **Missing Value Impact:** Numerous materials had to be excluded from the analysis due to missing values for one or more properties required for ratio calculations (Su, Bhn, A5, or Ro), potentially eliminating high-performing candidates from consideration.
- **Ratio Value Consistency:** The remarkably consistent Strength-to-Weight values (approximately 0.2) across aluminum alloys suggests possible data standardization, rounding effects, or measurement limitations that may obscure subtle but potentially important differences between materials.
- **Extreme Value Verification:** The exceptionally high Strength-to-Ductility values for annealed stainless steels (exceeding 30,000) warrant verification to ensure measurement accuracy before making critical design decisions based on these ratios.
- **Processing Detail Limitations:** Limited information about precise processing history (cold work percentage, exact aging parameters, etc.) restricts full understanding of why certain materials perform better in specific metrics.
- **Material Family Coverage:** While aluminum alloys and steels are well represented, limited data on other material families (titanium alloys, magnesium alloys, etc.) that could offer competitive property ratios constrains the comprehensiveness of selection recommendations.

## 6 Conclusions and Recommendations

The design ratio analysis yields several key conclusions to guide engineering material selection:

### Key Analysis Takeaways

The custom ratio analysis provides valuable insights for engineering decision-making:

- Material selection should be driven by identifying which property ratio is most critical for the specific application requirements, with clear understanding of the inevitable trade-offs.
- Heat treatment offers a powerful mechanism to shift material properties toward specific ratio performance targets, with annealing generally favoring Strength-to-Hardness and Strength-to-Ductility while age-hardening treatments (T6, T7) maximize Strength-to-Weight performance.

- Different material families show clear specialization patterns: aluminum alloys excel in Strength-to-Weight and Strength-to-Hardness ratios, while stainless steels dominate Strength-to-Ductility performance.
- Data quality limitations, particularly missing values and potential measurement consistency issues, require careful consideration when making engineering decisions based on these custom ratios.
- For critical applications, engineers should consider supplementing this ratio analysis with additional testing or verification of specific properties most crucial to their design requirements.

## 6.1 Engineering Applications

The custom ratio analysis provides specific guidance for real-world engineering applications:

### Practical Implementation Guidelines

Engineers can apply these findings in several ways:

- **Aerospace Structures:** Select 7075-T6/T651 aluminum alloys for optimal Strength-to-Weight performance in primary structural components.
- **Automotive Safety Systems:** Choose annealed SAE 303 series stainless steels for energy-absorbing components where deformation before failure is critical.
- **Consumer Electronics:** Consider 7000-series aluminum alloys for portable device frameworks requiring high strength and minimal weight.
- **Manufacturing Efficiency:** Select 1000-series aluminum in O-condition for components requiring extensive machining or forming operations while maintaining adequate strength.
- **Medical Implants:** Implement SAE 30310/30347 stainless steels where a combination of strength, ductility, and corrosion resistance is essential.

## 7 Appendix: Design Ratio Methodology

### Analysis Approach

The design ratio analysis employed these methodological steps:

#### 1. Ratio Definition:

- **Strength-to-Hardness ( $S_u/B_{hn}$ ):** Ultimate tensile strength divided by



Brinell hardness

- Strength-to-Ductility ( $S_u \times A_5$ ): Ultimate tensile strength multiplied by elongation percentage
- Strength-to-Weight ( $S_u/R_o$ ): Ultimate tensile strength divided by density

## 2. Data Processing:

- Removal of rows with NaN values in required properties
- Calculation of each ratio for remaining materials
- Sorting and ranking materials by each ratio

## 3. Visualization:

- Heat map generation to compare ratio values across materials
- Radar chart creation to visualize trade-offs between different ratios

## 4. Analysis:


- Identification of top-performing materials in each ratio
- Cross-ratio comparison to identify trade-off patterns
- Material family and heat treatment pattern recognition

# 8. Index-Based Material Comparison for Aluminum Alloys

## Key Observations from the Heatmap:


### • Consistency in Strength-to-Weight Ratio ( $S_u / R_o$ )

All materials have a Strength-to-Weight index  $\approx 0.2$  — nearly identical across the board.

 **Engineering Insight:** These aluminum alloys offer very similar structural efficiency per unit weight, making them excellent candidates for weight-sensitive applications (e.g., aerospace, automotive).


### • Variation in Strength-to-Ductility ( $S_u \times A_5$ )

There's a wide spread in the Strength-to-Ductility index, from around 5600 to 9380.

 **Engineering Insight:** Some alloys (like 2024-T4 and 2024-T351) show superior toughness, meaning they maintain high strength and deformability — crucial in crash-critical components or fatigue-prone environments.

### • Strength-to-Hardness ( $S_u / B_{hn}$ ) is Modestly Differentiated

Mostly between 3.6 and 4.0, with slight edge for 2024-T3.

 **Engineering Insight:** This suggests similar resistance to wear per unit strength, but 2024-T3 may handle surface stress slightly better. Good for riveted or bolted structures where localized hardness matters.

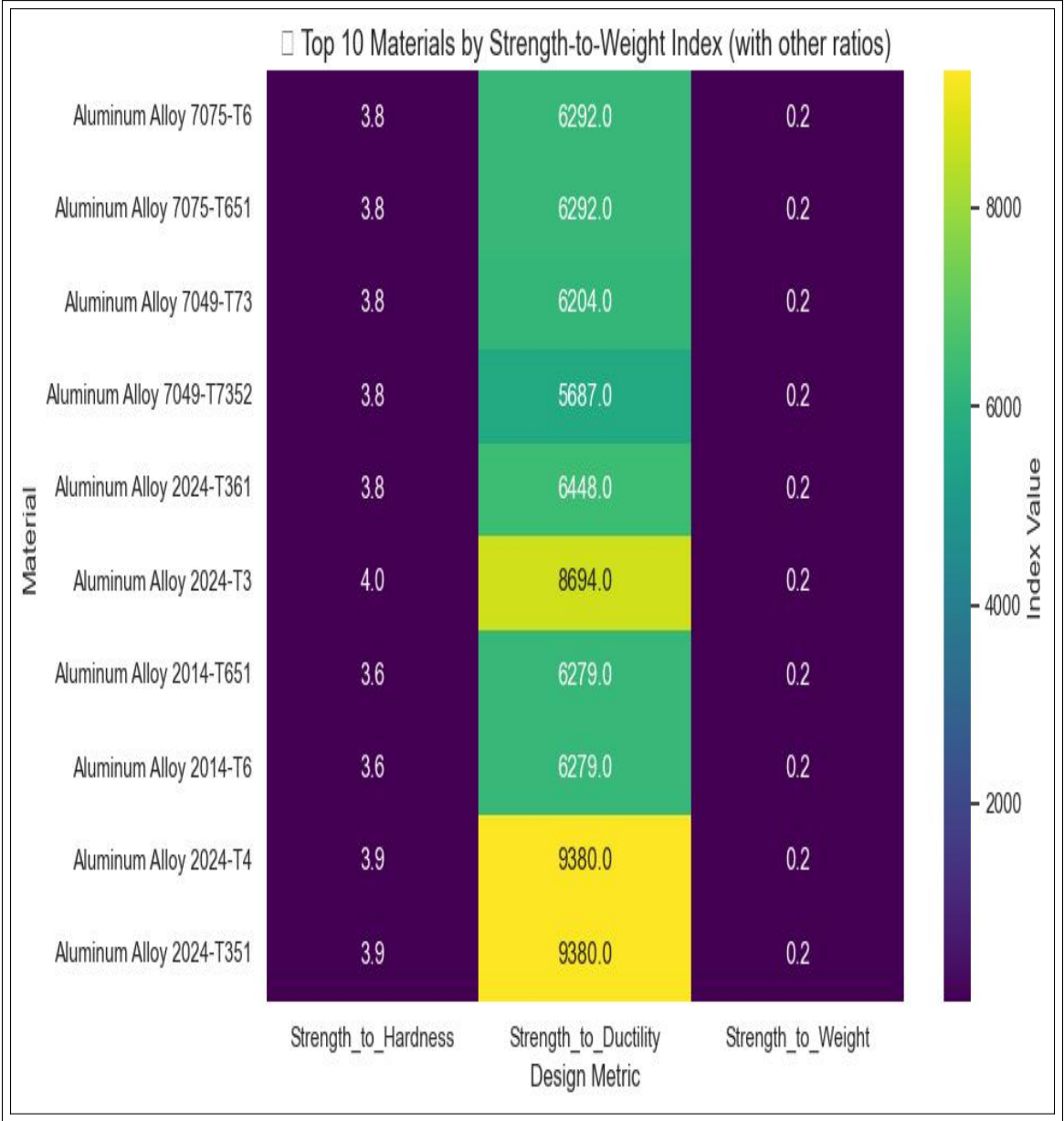


Figure 1: Heatmap of Key Performance Indexes for Aluminum Alloys ( $S_u/R_o$ ,  $S_u \times A_5$ ,  $S_u/B_{hn}$ )

Design Goal	Best Candidate(s)	Why
Lightweight structure	Any (all $\approx 0.2$ $S_u/R_o$ )	Excellent strength-to-weight across the board
Ductility + strength (tough)	2024-T4 / 2024-T351	Highest $S_u \times A_5$ values
Surface contact or wear zones	2024-T3	Slightly better $S_u/B_{hn}$ $\rightarrow$ better for fasteners/joints

Table 6: Material Selection Based on Performance Indexes

- **Aerospace fuselage panels:** Go for **2024-T351** — strong, tough, and light.
- **Automotive crash structures:** **2024-T4** or **7075-T6** offer strength with decent ductility.
- **Bike frames, tools:** If minimal deformation is acceptable, **7075-T651** gives rigidity and strength.

## 9. Trade-Off Analysis in Material Indexes

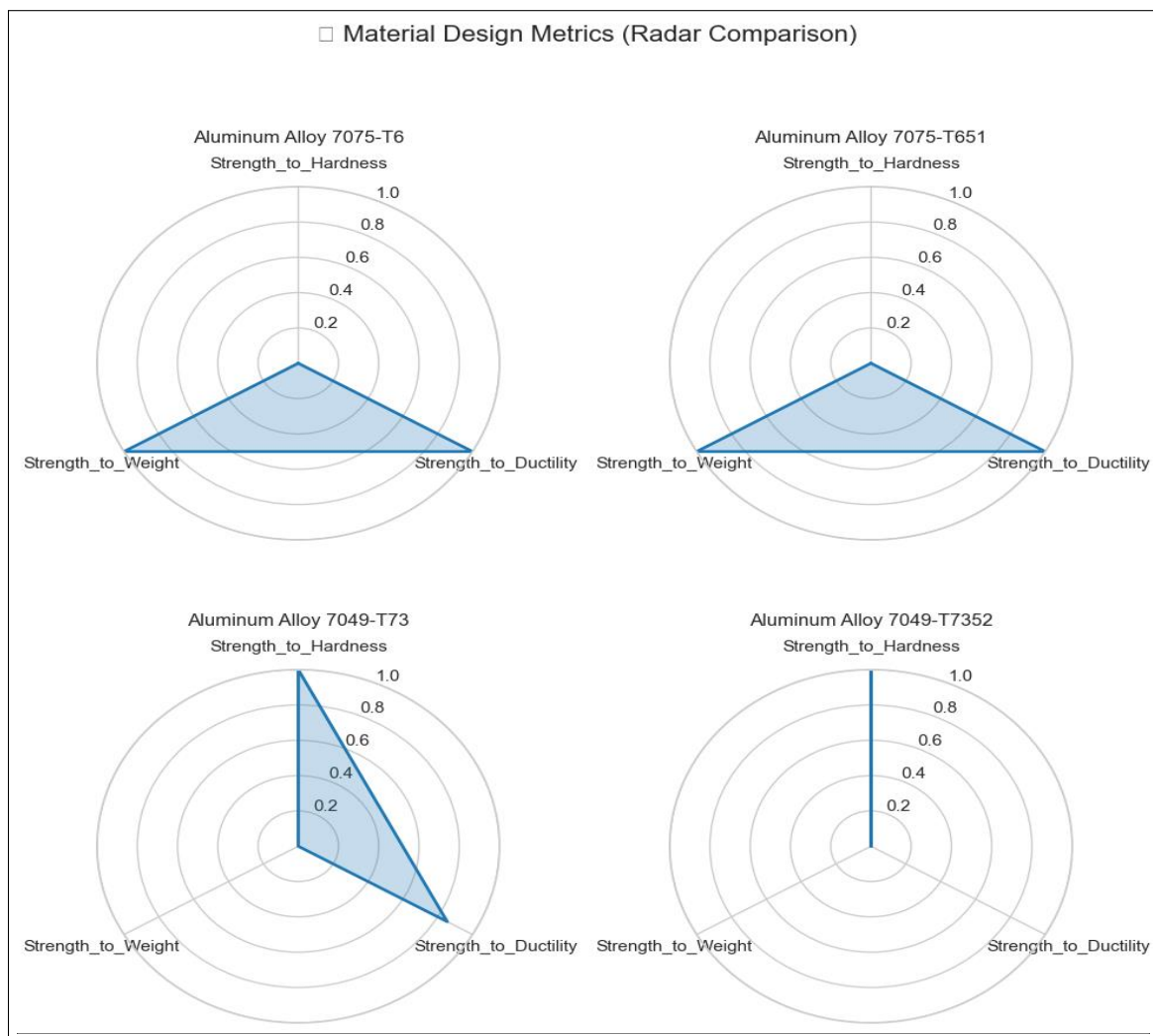


Figure 2: Trade-off Plot: Strength/Weight, Strength/Ductility, and Strength/Hardness across Alloys

### Key Trade-Off Observations:

- **High Strength/Weight & Strength/Ductility vs. High Strength/Hardness:** The plots reveal a clear inverse relationship between these ratios.


⚙️ [Material Behavior:](#)

- **7075 Alloys** excel in Strength-to-Weight and Strength-to-Ductility, but lag in Strength-to-Hardness.
- **7049 Alloys** deliver peak Strength-to-Hardness, but underperform in the other two.

 **Key Insight:** Prioritize the most important ratio — it’s not feasible to optimize all three simultaneously with these materials.

• **Maximizing One Ratio vs. Balanced Trade-Offs (Within 7049 Series):**

- **7049-T7352:** Maximizes Strength-to-Hardness (value  $\approx 1.0$ ) at the cost of significantly reduced Strength/Weight and Ductility.
- **7049-T73:** Trades some Strength-to-Hardness to moderately improve other mechanical aspects.

 **Key Insight:** Extreme optimization of one ratio can critically compromise others — consider a balanced variant if multiple performance goals matter.

**Quick Comparison Table of Trade-Offs:**

Alloy	Strength/Weight	Strength/Ductility	Strength/Hardness
7075	High	High	Low
7049-T73	Low–Moderate	Low–Moderate	High
7049-T7352	Very Low	Very Low	Peak (1.0)

Table 7: Performance Trade-Offs Across Aluminum Alloys

**Key Takeaways:**

- **Material selection** depends on what performance goal is most critical (e.g., lightweight vs. wear resistance).
- **7049-T7352** is ideal for hardness-dominant environments but suffers significantly in ductility and weight-related properties.
- **7075** is better suited for high ductility and lightweight designs where surface hardness is less critical.