PART 2 – Cross Dataset Engineering Tasks

Task 10: Material Ranking by Multi-Criteria Score

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Abstract

This report presents an analysis of engineering materials based on Task 10 (Material Ranking by Multi-Criteria Score) of the materials dataset. We examine how different properties including ultimate tensile strength (Su), elongation at break (A5), density (Ro), and Poisson's ratio (mu) can be combined into a weighted scoring system. This multi-criteria approach identifies optimal materials for specific engineering applications by quantifying the inherent trade-offs between competing properties. The analysis provides critical insights for material selection while highlighting data quality considerations that engineers should account for when making design decisions based on this ranking methodology.

1 Introduction

The Multi-Criteria Approach to Material Selection

Engineering material selection frequently involves balancing competing properties to optimize performance for specific applications. This report presents a normalized scoring methodology that quantitatively evaluates materials based on weighted combinations of strength, ductility, density, and deformation characteristics. The multi-criteria score provides a systematic framework for comparing materials across different property dimensions, enabling more informed engineering decisions than single-property comparisons. By normalizing diverse properties to common scales and weighting them according to application requirements, this approach captures the complex trade-offs inherent in material selection processes.

2 Material Selection Insights

2.1 Multi-Criteria Score Methodology

The analysis employs a systematic approach to normalize and combine diverse material properties into a unified scoring system:

Score Calculation Methodology

The multi-criteria material ranking methodology follows these key steps:

- **Property Normalization**: Each property is normalized to a 0-1 scale to enable fair comparison despite different units and magnitudes:
  - Su (Ultimate Tensile Strength): Min-Max scaling where higher values are better
  - A5 (Elongation): Min-Max scaling where higher values are better
  - Ro (Density): Inverse Min-Max scaling where lower values are better (higher scores for lower density)
  - mu (Poisson's Ratio): Gaussian penalty function centered at mu=0.3, penalizing extreme values
- **Weighted Combination**: The normalized properties are combined using application-appropriate weights:
  - Su: 40% weight (w1 = 0.4)
  - A5: 30% weight (w2 = 0.3)
  - Ro: 20% weight (w3 = 0.2)
  - mu: 10% weight (w4 = 0.1)
- **Final Score Formula**:

  $$\text{Material\_Score} = w1 \times \text{Su\_norm} + w2 \times \text{A5\_norm} + w3 \times \text{Ro\_inv\_norm} + w4 \times \text{mu\_penalty}$$

This methodology provides a quantitative basis for evaluating the complex trade-offs between competing material properties, enabling more informed engineering decisions.

2.2 Top-Ranked Materials

The multi-criteria analysis reveals distinct material groups with complementary property profiles:

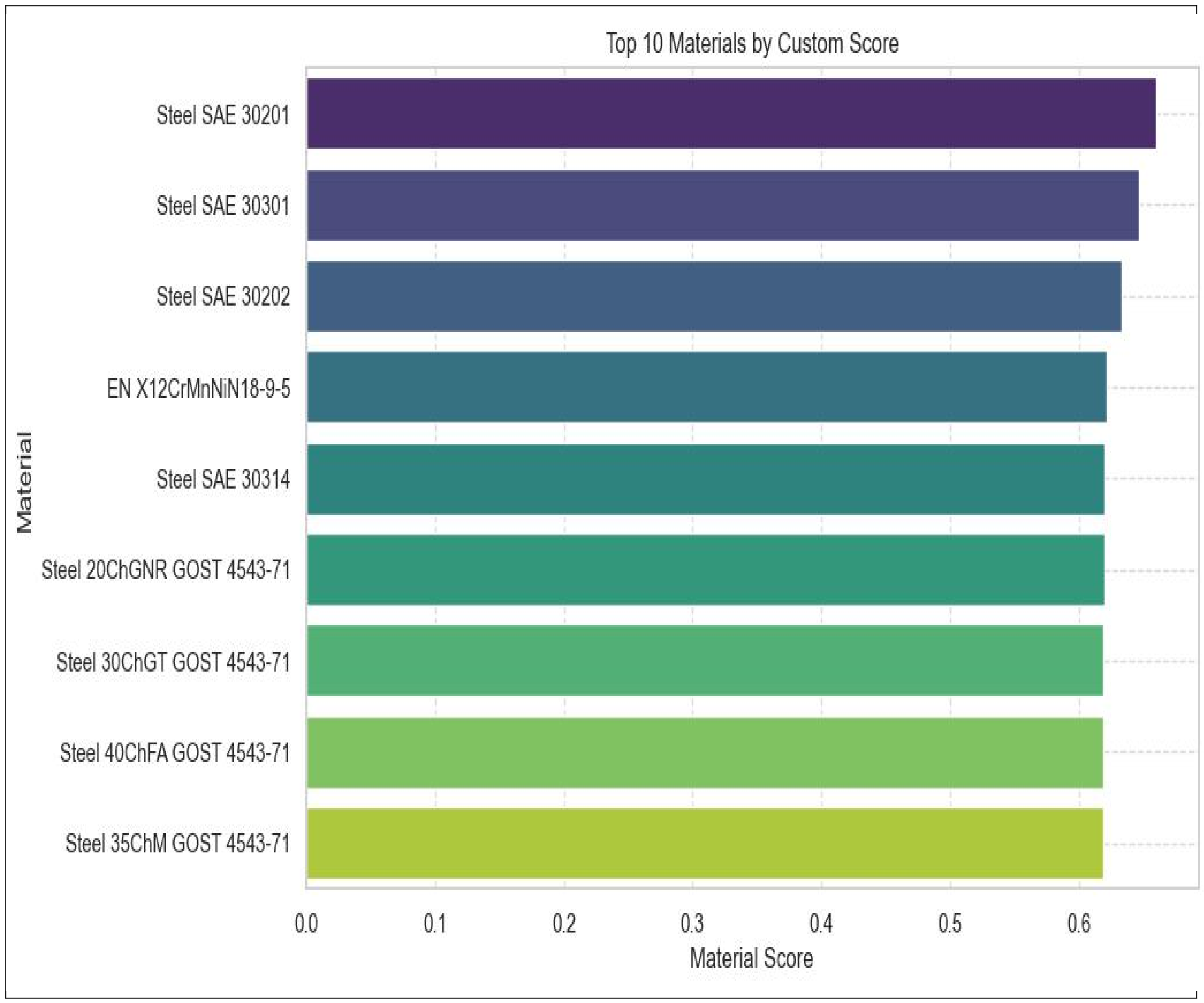

Figure 1: Top 10 Materials by Custom Score Analysis

Table 1: Top 10 Materials by Multi-Criteria Score

Material	**Su_norm**	**A5_norm**	**Ro_inv_nor**	**Score**	**Key Strength**
Steel SAE 30201	0.586	1.000	0.125	0.660	Exceptional ductility
Steel SAE 30301	0.553	1.000	0.125	0.646	Exceptional ductility
Steel SAE 30202	0.521	1.000	0.125	0.633	Exceptional ductility
EN X12CrMnNiN18-9-5	0.479	1.000	0.149	0.621	Balanced properties
Steel SAE 30314	0.487	1.000	0.125	0.620	Exceptional ductility
Steel 20ChGNR GOST 4543-71	1.000	0.293	0.157	0.619	Maximum strength
Steel 20ChGNR GOST 4543-71	1.000	0.293	0.157	0.619	Maximum strength
Steel 30ChGT GOST 4543-71	1.000	0.293	0.157	0.619	Maximum strength
Steel 40ChFA GOST 4543-71	1.000	0.293	0.156	0.619	Maximum strength
Steel 35ChM GOST 4543-71	1.000	0.293	0.155	0.619	Maximum strength

Material Group Comparison

The multi-criteria ranking identifies two distinct material categories with complementary property profiles:

- **SAE 300 Series Steels** (Ranks 1-5):
  - Moderate strength (Su_norm 0.48-0.59)
  - Maximum ductility (A5_norm = 1.000)
  - Moderate density (Ro_inv_norm 0.125-0.149)
  - Optimal Poisson's ratio behavior (mu_penalty = 1.000)
  - Primary advantage: exceptional elongation properties
- **GOST 4543-71 Steels** (Ranks 6-10):
  - Maximum strength (Su_norm = 1.000)
  - Limited ductility (A5_norm = 0.293)
  - Slightly better density (Ro_inv_norm 0.155-0.157)
  - Optimal to near-optimal Poisson's ratio (mu_penalty 0.998-1.000)
  - Primary advantage: superior tensile strength

This clear distinction illustrates the fundamental strength-ductility trade-off in engineering materials, with no material achieving maximum scores in both categories.

2.3 Property Distribution Visualization

Radar charts provide multidimensional visualization of how properties are distributed across top-ranked materials:

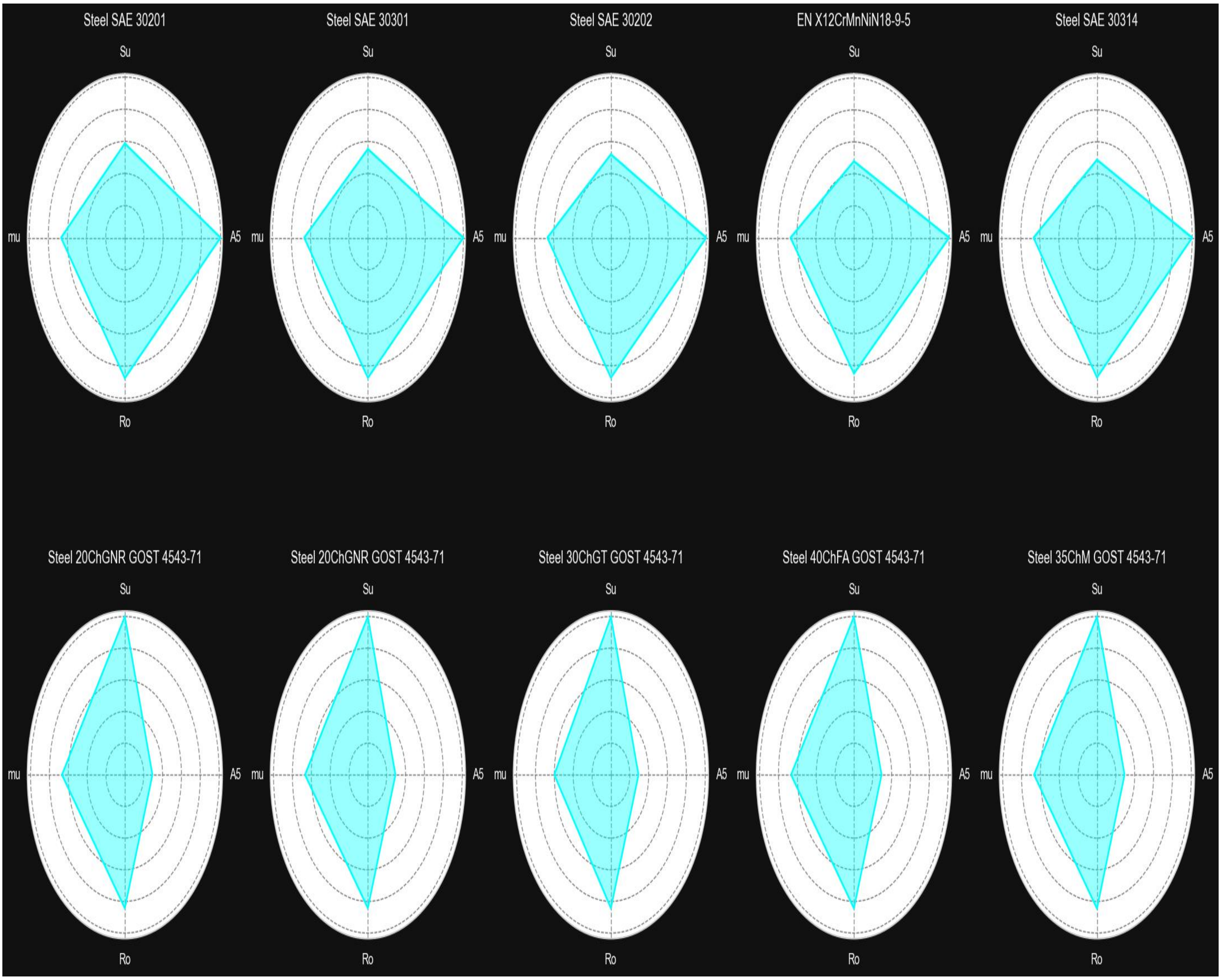

Figure 2: Radar Charts of Normalized Properties for Top 10 Materials

Multidimensional Property Analysis

The radar chart visualization reveals important patterns in the property distribution of top-ranked materials:

- **Complementary Property Profiles**:
  - SAE steels exhibit "kite-shaped" charts with maximum elongation but moderate strength
  - GOST steels show "triangle-shaped" charts with maximum strength but

limited elongation

- **Balanced Performance**: EN X12CrMnNiN18-9-5 demonstrates particularly well-balanced properties across all four dimensions, with better-than-average density compared to other SAE materials
- **Density Variation**: Limited variation in density (Ro_inv_norm) across top materials suggests this property has less influence on final ranking than strength and ductility
- **Poisson's Ratio Consistency**: Most top materials exhibit optimal Poisson's ratio behavior, indicating this property functions more as a screening criterion than a differentiator

The multidimensional visualization reinforces the fundamental trade-off between strength and ductility, with no material achieving maximum performance in both dimensions.

3 Application-Specific Recommendations

Based on the multi-criteria analysis, specific materials emerge as optimal for different engineering applications:

Table 2: Material Recommendations by Application Type

Application Type	Recommended Material	Selection Rationale
Static High-Load Structures	20ChGNR, 40ChFA, 35ChM GOST 4543-71	Maximum strength (Su_norm = 1.000) even at lower ductility
Dynamic/Flexible Components	EN X12CrMnNiN18-9-5	Excellent elongation and strength balance with improved density
General Structural Use	Steel SAE 30201, 30301	Well-rounded properties with no major weakness
Wear-Resistant Components	40ChFA, 35ChM GOST 4543-71	Good hardness potential from high strength; acceptable friction
Lightweight Structures	SAE 30202, SAE 30301	Balanced weight-to-strength ratio
Precision Springs/Flex Elements	EN X12CrMnNiN18-9-5	High ductility ensures flexibility; strength prevents permanent deformation
High-Stress Gears/Shafts	20ChGNR, 30ChGT GOST 4543-71	High load-bearing with acceptable toughness trade-off

Application-Specific Selection Guidelines

The multi-criteria score analysis provides clear guidelines for application-specific material selection:

- **Crash Energy Absorption**: SAE 300 series steels with maximum elongation (A5_norm = 1.000) are optimal for applications requiring controlled deformation and energy absorption, such as automotive crash structures
- **Static Structural Components**: GOST 4543-71 steels with maximum strength (Su_norm = 1.000) excel in applications where dimensional stability and load-bearing capacity are primary concerns
- **Balanced Performance Requirements**: EN X12CrMnNiN18-9-5 provides an exceptional balance of properties for applications requiring good performance across multiple dimensions
- **Cyclic Loading Applications**: Materials with higher elongation scores are better suited for applications experiencing repeated loading and unloading
- **Manufacturing Considerations**: High-ductility materials typically offer better formability, which may influence selection for components requiring significant forming operations

These application-specific guidelines translate the quantitative multi-criteria scores into practical engineering selection criteria.

4 Data Quality Observations

4.1 Missing Data Patterns

The multi-criteria analysis reveals important data quality considerations that must be accounted for when interpreting the material rankings:

Data Completeness and Accuracy

Several data quality issues impact the reliability of the multi-criteria rankings:

- **Missing pH Values**: All top-ranked materials show NaN values for pH, indicating incomplete environmental compatibility data that would be important for applications in corrosive environments
- **Potential Data Duplication**: Steel 20ChGNR GOST 4543-71 appears twice with identical properties, suggesting possible data entry errors or duplicate records requiring verification
- **Measurement Scale Variations**: The original properties (Su, A5, Ro, mu)

span vastly different scales and units, highlighting the importance of appropriate normalization to enable fair comparison

- **Limited Environmental Data**: The lack of comprehensive pH data limits the ability to incorporate corrosion resistance into the multi-criteria score for applications requiring chemical compatibility

These data quality observations should be considered when applying the material rankings to critical engineering decisions.

4.2 Methodological Limitations

The multi-criteria scoring approach has inherent methodological considerations that engineers should be aware of:

Weighting Sensitivity and Methodological Considerations

The multi-criteria ranking methodology introduces several important considerations:

- **Weighting Sensitivity**: The final rankings are influenced by the chosen weights (0.4, 0.3, 0.2, 0.1) for different properties. Different applications might require different weight distributions
- **Normalization Effects**: The min-max scaling approach assumes linear relationships between raw property values and their desirability, which may not always match engineering reality
- **Poisson's Ratio Modeling**: The Gaussian penalty function for mu effectively acts as a screening filter rather than a continuous score discriminator
- **Missing Properties**: Important engineering properties like fracture toughness, fatigue resistance, and corrosion behavior are not included in the current scoring model
- **Score Clustering**: The top GOST steels show nearly identical scores (0.619) despite potentially meaningful differences in specific properties

Understanding these methodological considerations helps engineers apply the material rankings appropriately within their specific design contexts.

5 Conclusions and Recommendations

The multi-criteria material ranking analysis yields several key conclusions to guide engineering material selection:

Key Multi-Criteria Ranking Takeaways

The comprehensive analysis of materials using normalized multi-criteria scoring reveals:

- **Property Trade-offs**: There is a clear inverse relationship between strength and ductility among top-ranked materials, with no material achieving maximum performance in both dimensions
- **Distinct Material Groups**: Materials cluster into distinct performance categories—SAE 300 series dominated by ductility and GOST steels excelling in strength
- **Application Matching**: Material selection should align with application requirements, with ductility-focused materials for dynamic applications and strength-focused materials for static structural components
- **Balanced Performers**: EN X12CrMnNiN18-9-5 emerges as an exceptionally balanced material, offering good performance across all evaluated properties
- **Data Quality Awareness**: Missing pH data and potential duplicate records suggest caution when applying these rankings to applications where corrosion resistance is critical

5.1 Engineering Implications

The multi-criteria scoring approach provides valuable guidance for engineering design and material selection processes:

Practical Engineering Applications

Engineers can apply these findings in several ways:

- **Quantified Trade-off Assessment**: Use normalized scores to objectively evaluate the property trade-offs inherent in material selection decisions
- **Customized Weighting**: Adjust property weights based on specific application requirements to generate application-optimized material rankings
- **Multidimensional Visualization**: Employ radar charts to communicate complex property profiles to design teams and stakeholders
- **Gap Identification**: Identify specific property shortcomings in otherwise promising materials to guide further material development or modification
- **Decision Support**: Integrate multi-criteria scoring into formal decision matrices for material selection in complex engineering systems

6 Appendix: Multi-Criteria Scoring Methodology

Mathematical Framework

The multi-criteria material scoring follows this mathematical framework:

1. **Property Normalization**:
   - For properties where higher values are better (Su, A5):
   $$\text{Normalized Value} = \frac{\text{Value} - \text{Min}}{\text{Max} - \text{Min}}$$
   - For properties where lower values are better (Ro):
   $$\text{Normalized Value} = 1 - \frac{\text{Value} - \text{Min}}{\text{Max} - \text{Min}}$$
   - For properties with ideal mid-range values (mu):
   $$\text{Penalty Function} = \exp(-20 \times (\text{mu} - 0.3)^2)$$
2. **Weighted Score Calculation**:
   $$\text{Material\_Score} = 0.4\times\text{Su\_norm}+0.3\times\text{A5\_norm}+0.2\times\text{Ro\_inv\_norm}+0.1\times\text{mu\_penalty}$$
3. **Material Ranking** by descending Material_Score value

This systematic approach enables quantitative comparison of materials with diverse property profiles, providing an objective basis for engineering material selection.

Executive Summary

Material Selection Insight: Most top-performing steels balance **tensile strength** and **ductility** well, with minor trade-offs in **density** and **friction**.

High-Strength Materials: Steels like **20ChGNR** and **40ChFA** show outstanding ultimate strength but lower ductility, making them ideal for static, high-load structures.

Balanced Performance: EN X12CrMnNiN18-9-5 achieves excellent synergy between ductility and strength, making it suitable for dynamic or flexible designs.

Best Material by Application

Application Type	Key Requirement	Best Material(s)	Reason
Static High-Load Structures	High Ultimate Strength (Su)	20ChGNR, 40ChFA, 35ChM GOST 4543-71	Maximum strength even at lower ductility
Dynamic / Flexible Components	High Ductility (A5) + Good Strength	EN X12CrMnNiN18-9-5	Excellent elongation and strength balance
General Structural Use	Balanced Strength, Ductility, Density	SAE 30201, 30301, 30202, 30314	Well-rounded properties; no major weaknesses
Wear-Resistant Components	High Strength + Moderate Friction (μ)	40ChFA, 35ChM GOST 4543-71	Good hardness and strength; tolerable friction
Lightweight Structures	Lower Density (Ro) + Decent Strength	SAE 30202, SAE 30301	Good weight-to-strength performance
Precision Springs / Flex Elements	High Ductility (A5) + Strength	EN X12CrMnNiN18-9-5	Ductility ensures flexibility; strength prevents deformation
High-Stress Gears / Shafts	Very High Strength; Low Ductility Tolerable	20ChGNR, 30ChGT GOST 4543-71	High load-bearing with toughness trade-off

Quick Insights

If ductility is your main concern ⇒ **EN X12CrMnNiN18-9-5** is your best choice.

If brute strength is needed ⇒ **20ChGNR** and **40ChFA** dominate.

If all-around performance is preferred ⇒ Go with **SAE steels** (30201, 30301, etc.).