Modeling of Necking Area Reduction of Carbon Steel in Hydrogen Environment Using Machine Learning Approach

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Introduction

- ➢ Natural gas transport favors low carbon and alloy pipelines for their cost-effectiveness, weldability, longevity, and strength.
- ➢ Repurposing gas pipelines for hydrogen: Address regulatory, safety, and HE challenges.
- ➢ Addressing HE in Pipelines: Traditional mitigation strategies face adaptation challenges:

  - **Specialty Alloys**: Efficient, yet require costly specialized production.
  - **Protective Coatings:** Offer barriers, but come with expense and infrastructure modifications.
- ➢ Evaluating steel's embrittlement is resource-intensive; machine learning offers a more efficient, cost-effective solution.

Objectives

- ➢ Utilize ML to analyze hydrogen behavior in low carbon and low-alloy steels under high pressures.
- ➢ Evaluate several ML techniques to best predict HE's impact on mechanical properties, especially reduction in area.
- ➢ Provide guidance on material selection for hydrogen pipeline construction based on steel behavior in hydrogen environments.

Methodology

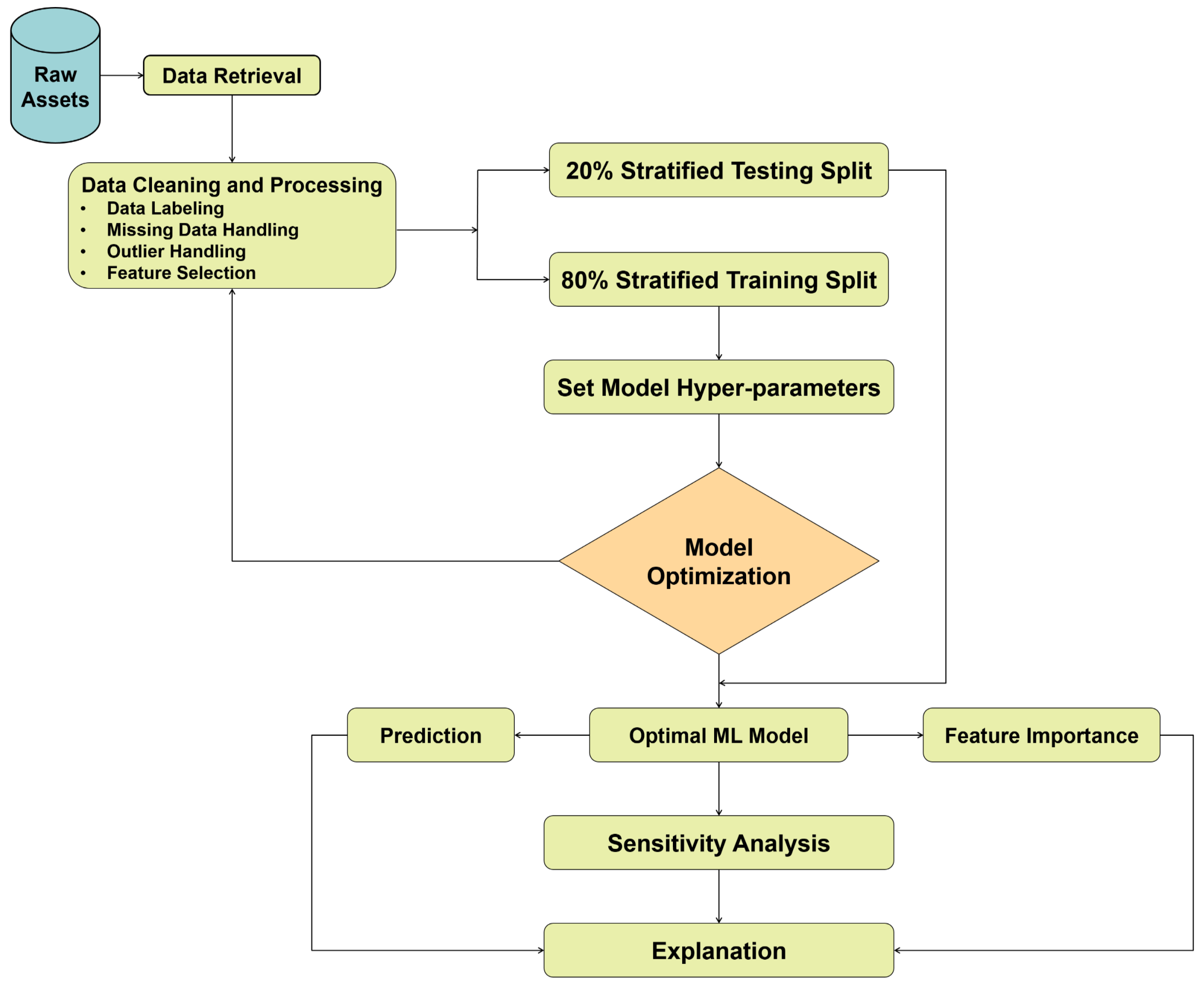


Fig. 1. Framework for Data Collection, Preparation, and Analysis.

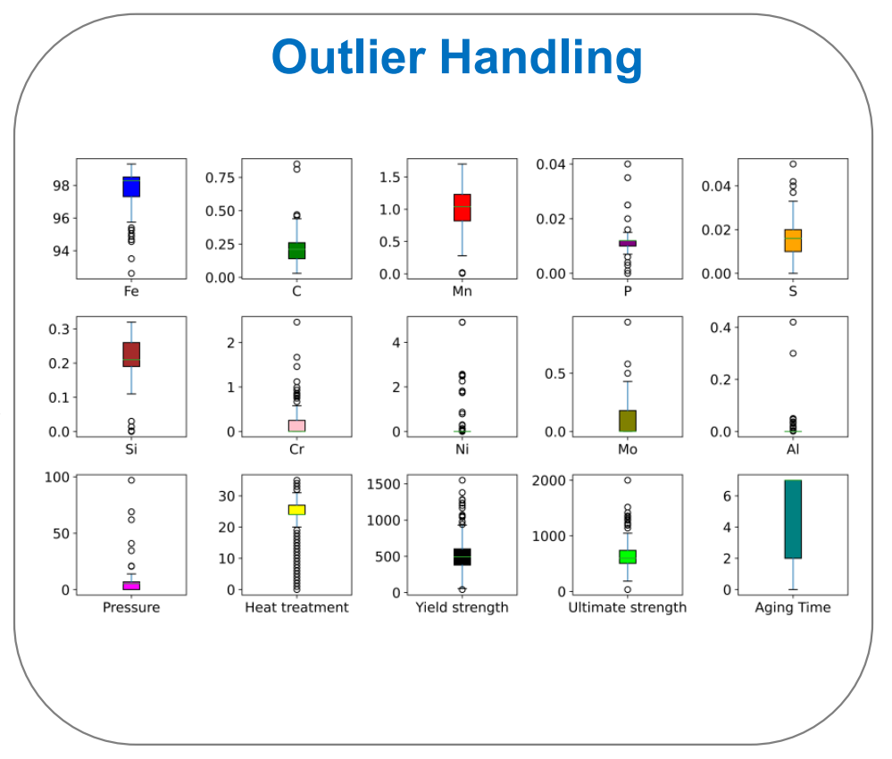
Results and Discussions

Data Processing

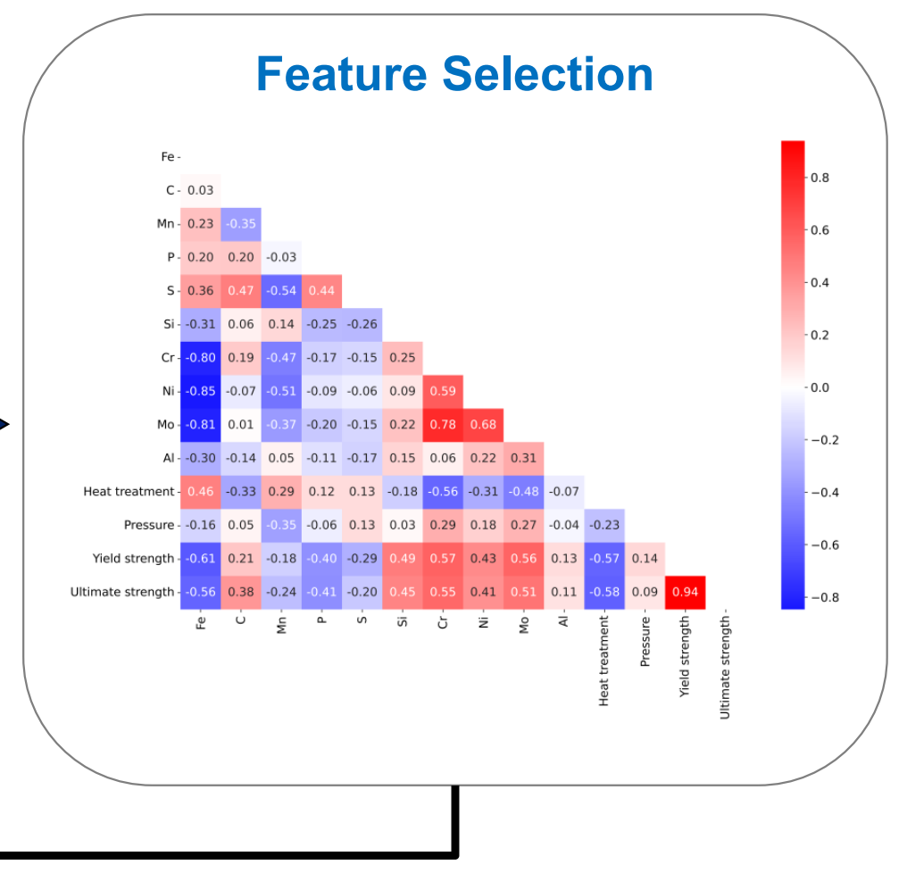
Database Summary

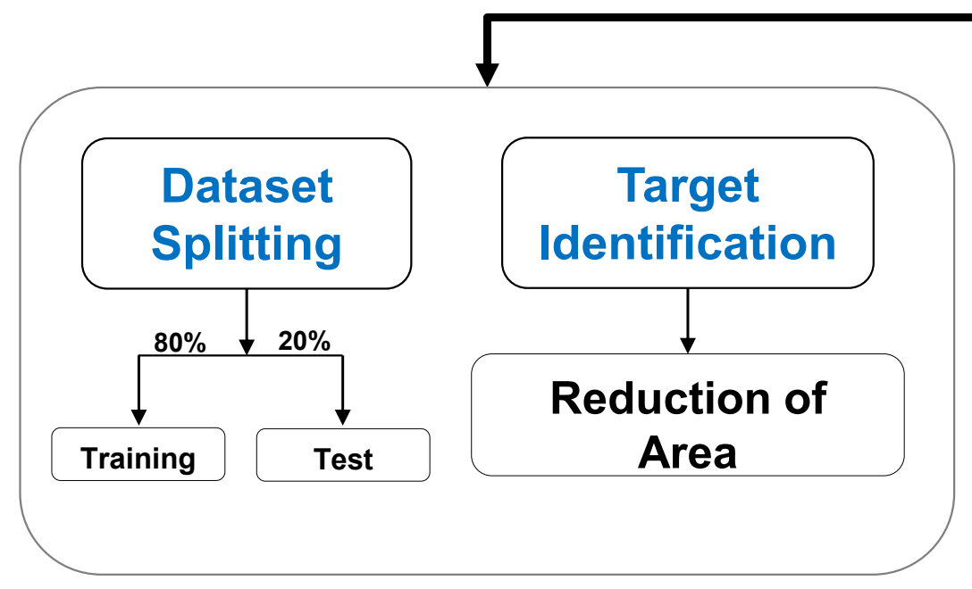
Categories	Parameters	Data Range (Minimum/Maximum)	Mean	Standard Deviation	Units
Chemical Properties	Iron (Fe)	92.61/99.31	97.812	1.131	%
	Carbon (C)	0.03/0.85	0.218	0.145	%
	Manganese (Mn)	0.007/1.70	1.025	0.352	%
	Phosphorous (P)	0.00/0.04	0.012	0.006	%
	Sulfur (S)	0.00/0.05	0.016	0.010	%
	Silicon (Si)	0.00/0.32	0.188	0.094	%
	Chromium (Cr)	0.00/2.46	0.266	0.455	%
	Nickel (Ni)	0.00/4.91	0.264	0.763	%
	Molybdenum (Mo)	0.00/0.94	0.087	0.156	%
	Aluminum (Al)	0.00/0.42	0.013	0.058	%
Mechanical Properties	Yield Strength (Su)	41.40/1550	529.95	249.764	MPa
	Ultimate Strength (Sy)	35/ 2000	653.047	256.539	MPa
	Reduction of Area (RA)	6.50/96.00	55.489	18.626	%
Test Conditions	Aging Time	0.00/7.00	4.852	2.971	Day
	Hydrogen Partial Pressure	0.10/97.00	13.125	23.246	MPa
	Strain Rate	2e-6/8e-3	2.43e-4	7.30e-4	s^{-1}
	Heat Treatment	Different heating treatment	-	-	-
	Product Form	Various sources*	-	-	-
	Hold Stress	0.00/9.00	6.483	3.059	MPa

Outlier Handling



Feature Selection





Machine Learning Model

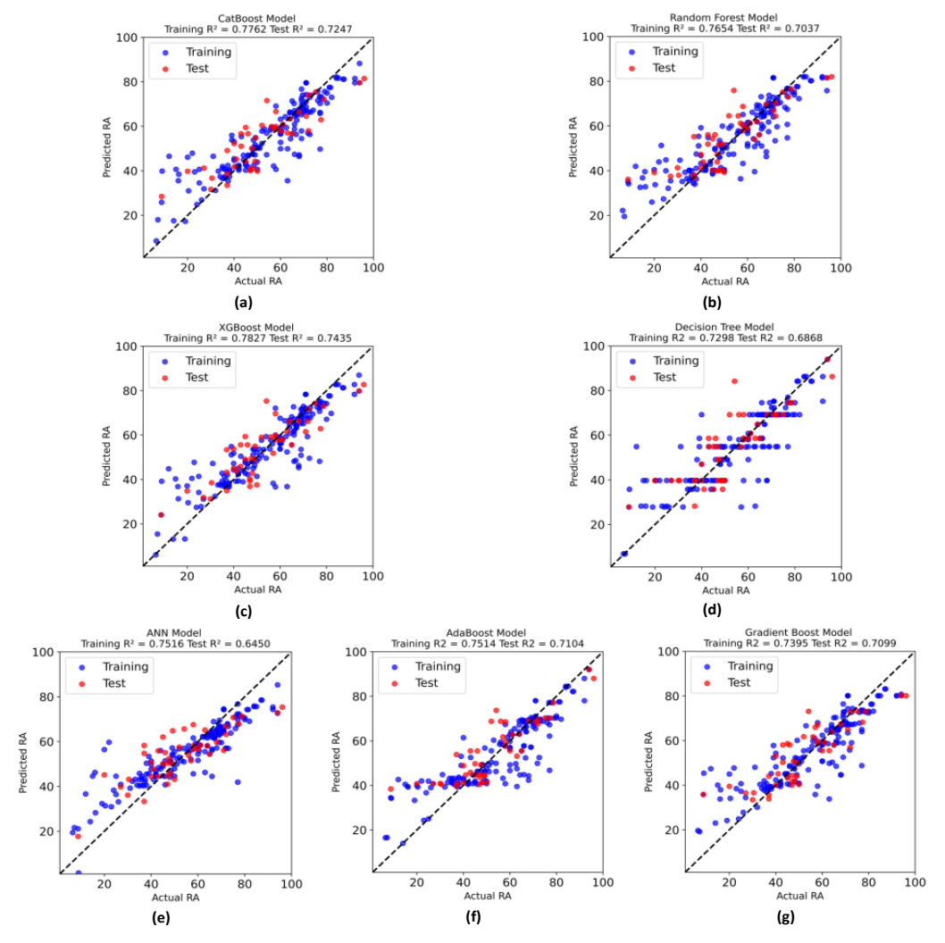


Fig. 2: Comparison of correlations between Actual RA and Predicted RA of seven ML models

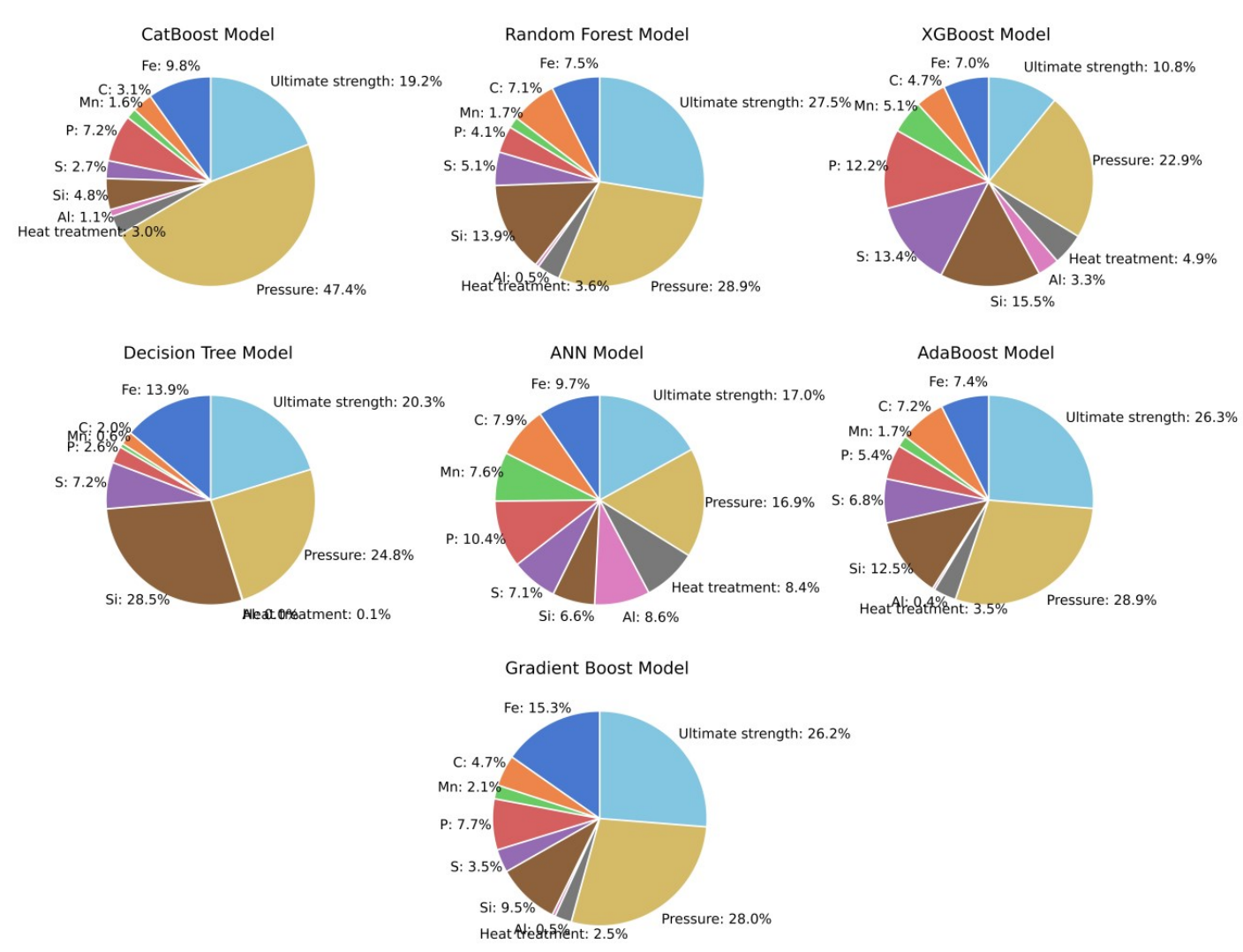


Fig. 3: Comparison of different features in predicting reduction of area using seven machine learning models

Performance Evaluation

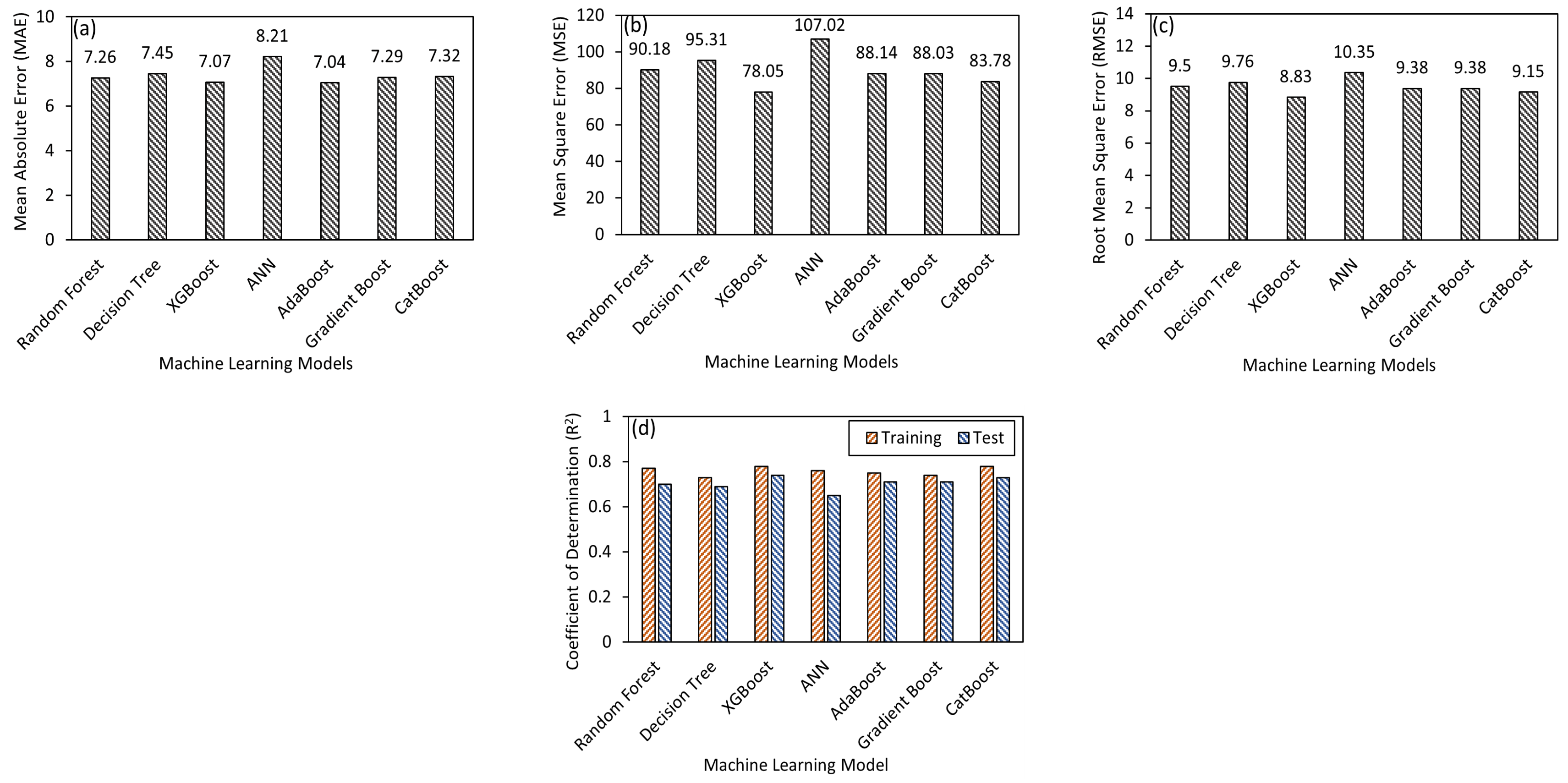


Fig. 4: Comparison of ML models performance based on (a) MAE, (b) MSE, (c) RMSE, and (d) R2

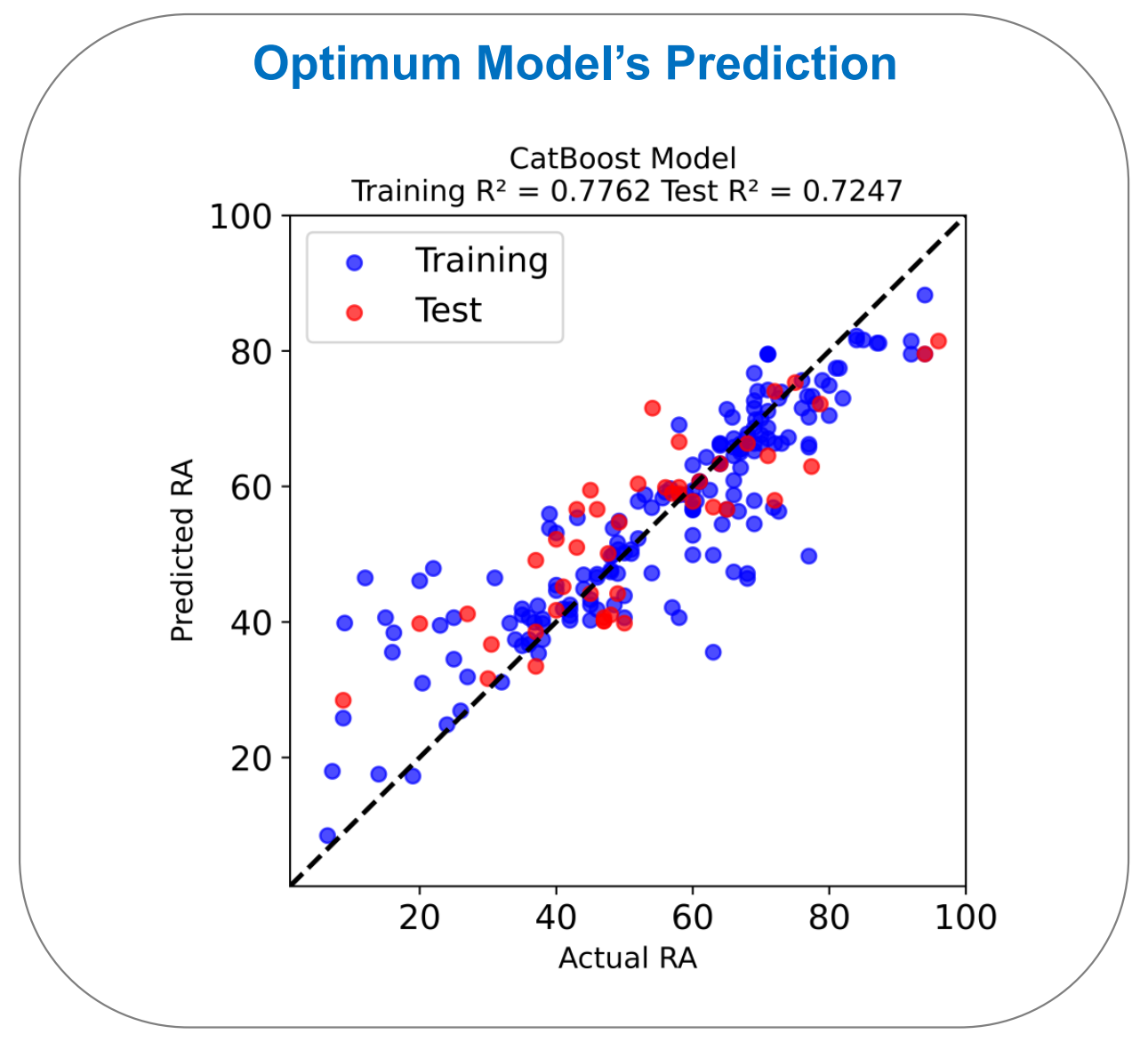
Optimum Model Selection

Model Name	Coefficient of Determination		MSE	RMSE	MAE	Pressure	Su	Fe	C	Si	S	P	Al	Mn	HT*
	Training R^2	Test R^2													
RF	0.77	0.70	90.18	9.50	7.26	1	2	4	5	3	6	7	10	9	8
DT	0.73	0.69	95.31	9.76	7.45	1	2	4	7	8	9	3	10	5	6
XGBoost	0.78	0.74	78.05	8.83	7.07	1	5	6	9	2	3	4	10	7	8
ANN	0.75	0.65	108.04	10.39	8.18	1	2	4	7	10	9	3	5	8	6
AdaBoost	0.75	0.71	88.14	9.38	7.04	1	2	4	6	3	5	7	10	9	8
GB	0.74	0.71	88.03	9.38	7.29	1	2	3	6	4	7	5	10	9	8
CatBoost	0.78	0.73	83.78	9.15	7.32	1	2	3	6	5	8	4	10	9	7
Average	0.76	0.70	90.07	9.48	7.38	1.0	2.4	4.0	6.6	5.0	6.7	4.7	9.3	8.0	7.3

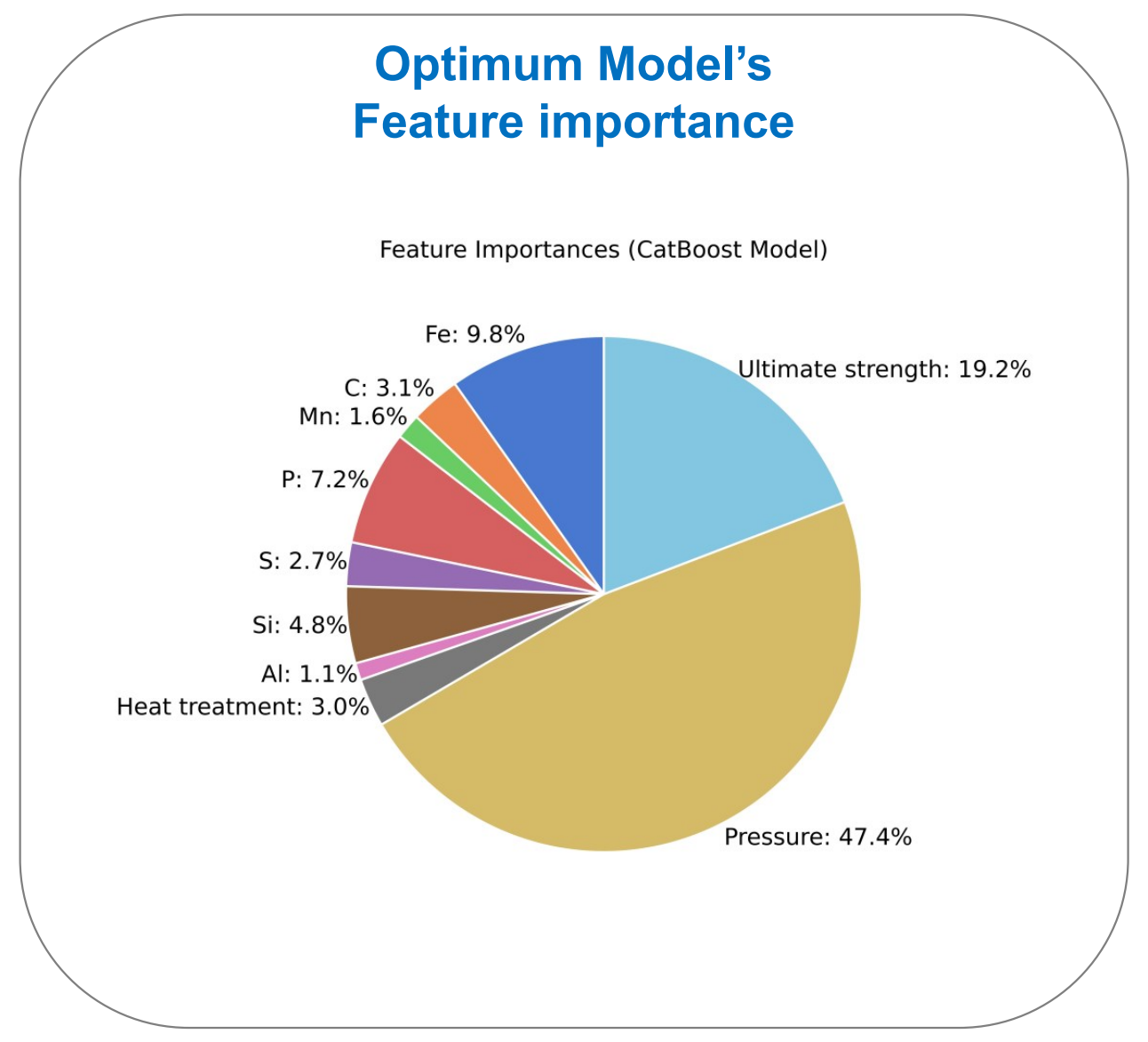
*** Heat Treatment**

CatBoost Model

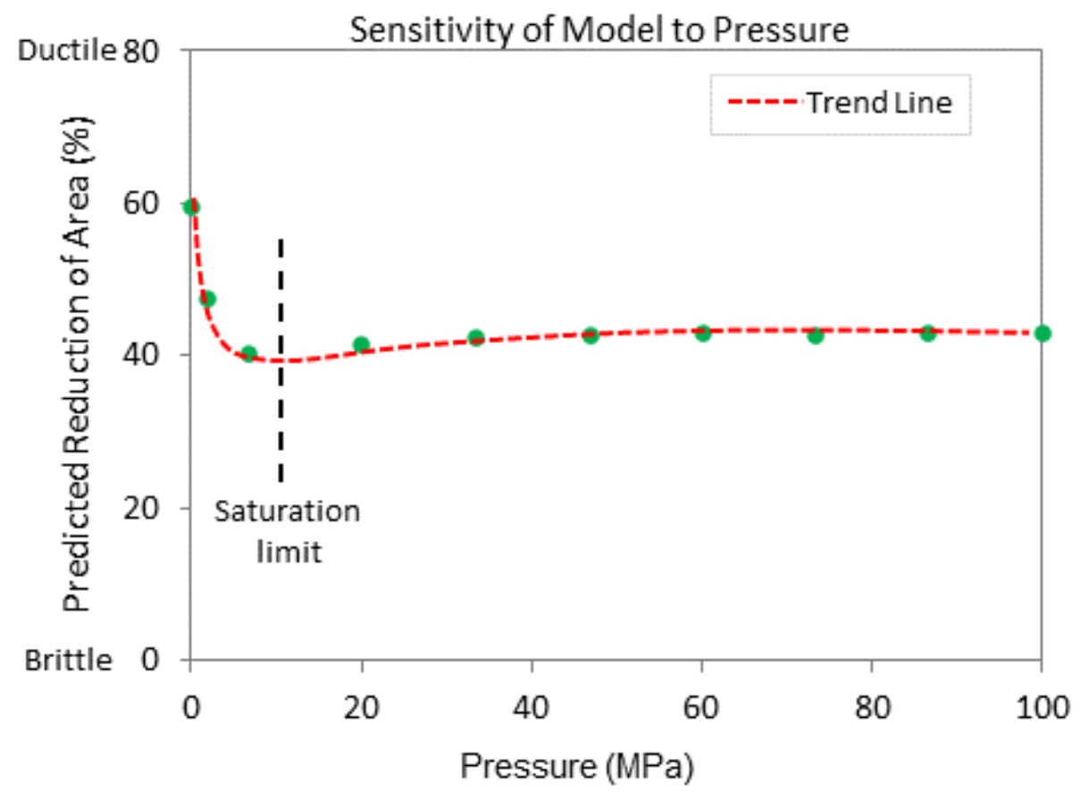
Optimum Model's Prediction

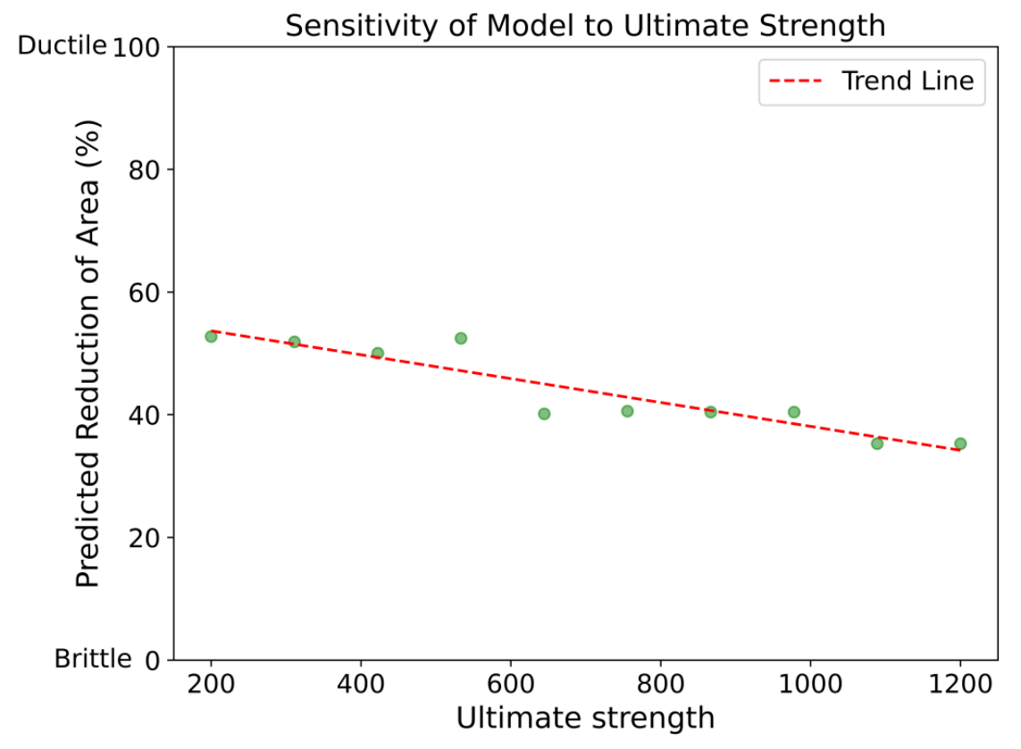


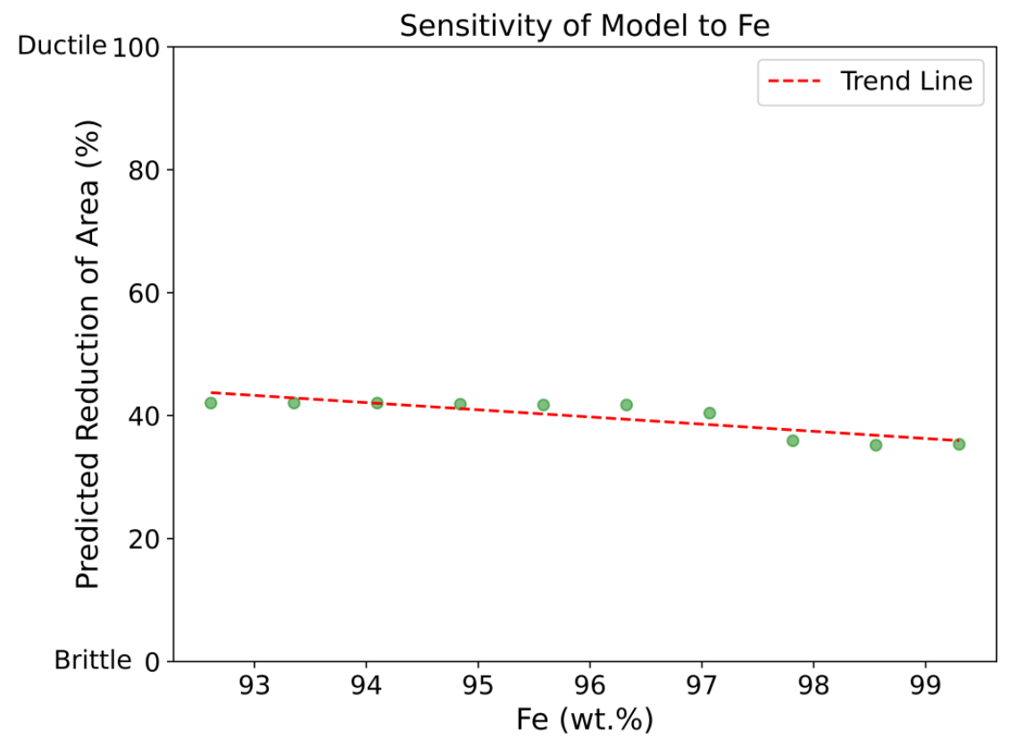
Optimum Model's Feature importance



Model Sensitivity Analysis







Conclusions

- ➢ CatBoost Model predicts hydrogen embrittlement in steel with MAE: 7.32, MSE: 83.78, RMSE: 9.15 (Training R2: 77.62%, Testing R2: 72.50%).
- ➢ Top Influencers: Pressure (47.4%) and UTS (19.2%) are critical, with elemental contributions from Iron, Phosphorus, and Silicon.
- ➢ Minor Elements: Mn, Al, and S have a combined, yet noteworthy impact.
- ➢ Application: Provides insights for material optimization, reducing hydrogen-induced risks.

References

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