

Supplementary Materials

A federated learning–driven data fusion strategy for the hardenability prediction of gear steel

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Supplementary Table 1. Implementation details of the federated MRAN-J9 training procedure.

Category	Parameter	Value
Federated training	Global communication rounds	100
Federated training	Local epochs per round	80
Federated training	Local early-stopping patience	10 epochs
Federated training	Global early-stopping patience	20 rounds
Optimization	Optimizer	AdamW
Optimization	Learning rate	0.001
Optimization	Batch size	128
Optimization	Weight decay	5×10^{-5}
Optimization	AdamW betas	0.9, 0.999
Optimization	Gradient clipping max norm	0.5
FedProx	Proximal coefficient μ	0.005
Adaptive aggregation	Balancing coefficient α	0.5
Loss function	Huber loss δ	1.0
Regularization	Gaussian input noise	$\sigma=0.003$
Regularization	Gradient noise	$\sigma=1 \times 10^{-5}$

Supplementary Table 2. Statistical evaluation of the dataset

Clients	Minimum (HRC)	Maximum (HRC)	Median (HRC)	Mean (HRC)	Standard deviation (HRC)
Client 1	28.50	43.63	35.91	35.79	2.81
Client 2	28.32	43.66	35.62	35.54	2.77
Client 3	27.31	44.41	35.85	35.81	2.86
Client 4	27.45	43.67	35.81	35.71	2.78
Validation set	27.45	44.20	35.90	35.69	2.90

Supplementary Table 3. Summary of results for individual client baseline models

Models	Client 1		Client 2		Client 3		Client 4	
	R²	RMSE (HRC)	R²	RMSE (HRC)	R²	RMSE (HRC)	R²	RMSE (HRC)
KNN	0.60	1.83	0.57	1.80	0.50	2.10	0.59	1.70
LR	0.65	1.71	0.59	1.75	0.56	1.96	0.57	1.74
RR	0.65	1.71	0.59	1.75	0.56	1.96	0.57	1.74
SVM	0.70	1.60	0.63	1.66	0.59	1.89	0.61	1.65
GBDT	0.72	1.54	0.57	1.81	0.64	1.77	0.66	1.54
XGB	0.76	1.41	0.65	1.61	0.65	1.74	0.59	1.69
RF	0.77	1.40	0.64	1.63	0.66	1.72	0.68	1.50
LGBM	0.78	1.31	0.65	1.62	0.67	1.70	0.67	1.53
MRAN	0.79	1.32	0.68	1.55	0.68	1.67	0.72	1.41

Supplementary Table 4. Performance comparison between locally trained deep learning baselines and the proposed federated MRAN-J9 framework across four clients

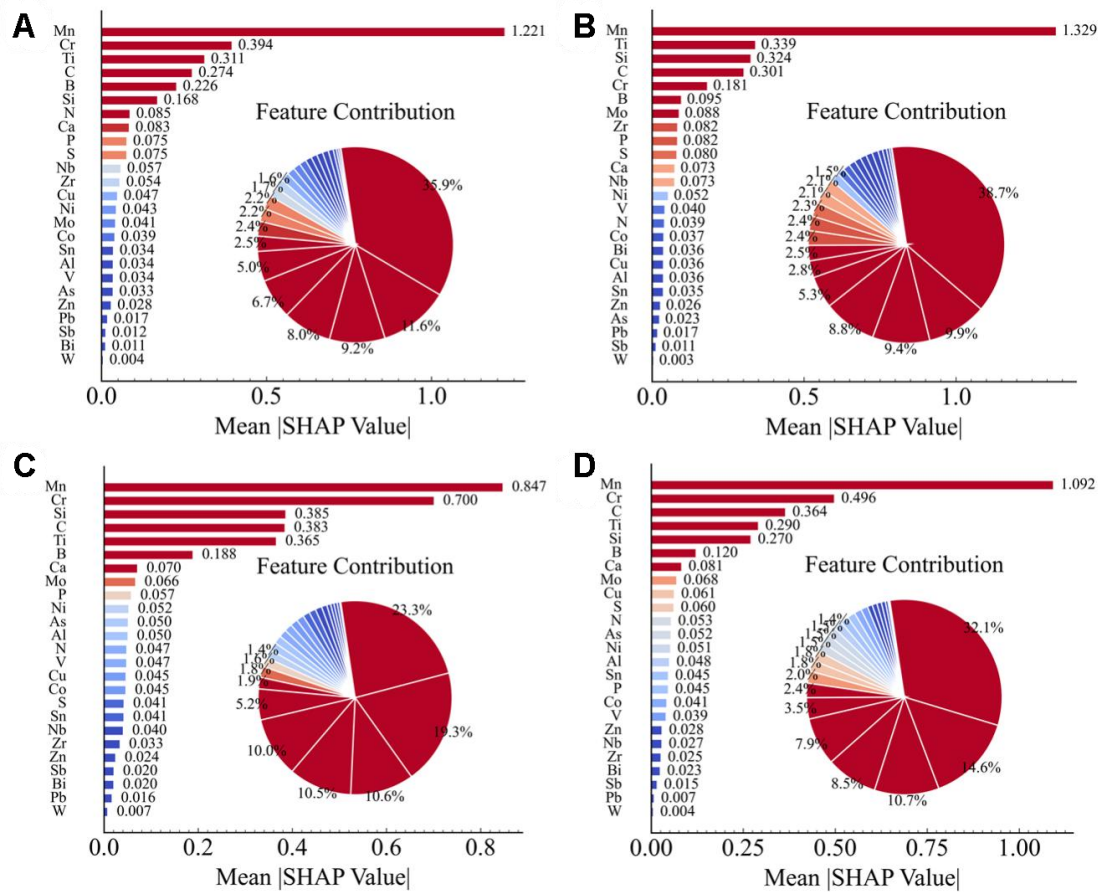
Model	Training Paradigm	Client 1 (R²)	Client 2 (R²)	Client 3 (R²)	Client 4 (R²)
1D-CNN	Local only	0.66	0.51	0.57	0.55
MLP-5	Local only	0.69	0.61	0.60	0.66
SE-MLP	Local only	0.75	0.60	0.63	0.62
This work	Local only	0.79	0.68	0.68	0.72
This work	Federated	0.88	0.80	0.84	0.83

Supplementary Table 5. Architectural ablation results of MRAN-J9 under a purely local setting

Model	Client 1 (R²)	Client 2 (R²)	Client 3 (R²)	Client 4 (R²)	Average (R²)
MRAN-J9	0.79	0.68	0.68	0.72	0.72
Without residual connection	0.73	0.63	0.64	0.63	0.66
Without ECA attention	0.77	0.63	0.65	0.61	0.67
Without noise regularization	0.76	0.63	0.65	0.63	0.67
Without feature aggregation	0.74	0.64	0.62	0.64	0.66

Supplementary Table 6. Performance comparison of different federated learning aggregation strategies on the test sets

Method	Client 1 (R²/RMSE)	Client 2 (R²/RMSE)	Client 3 (R²/RMSE)	Client 4 (R²/RMSE)	Global Test (R²/RMSE)
FedAvg	0.82 / 1.28 HRC	0.74 / 1.41 HRC	0.77 / 1.42 HRC	0.77 / 1.28 HRC	0.85 / 1.12 HRC
FedProx	0.82 / 1.23 HRC	0.76 / 1.40 HRC	0.78 / 1.38 HRC	0.77 / 1.29 HRC	0.85 / 1.16 HRC
This work	0.88 / 1.03 HRC	0.80 / 1.25 HRC	0.84 / 1.19 HRC	0.83 / 1.34 HRC	0.88 / 0.99 HRC



Supplementary Figure 1. Feature importance for the dataset of four clients. (A–D) show the ranking of feature importance based on SHAP values for the dataset of clients 1 through 4, respectively.