2024 Fall Conference of the KWJS

Prediction of Welding Strength based on Friction Stir Welding (FSW) Tool Temperature and Machine Learning

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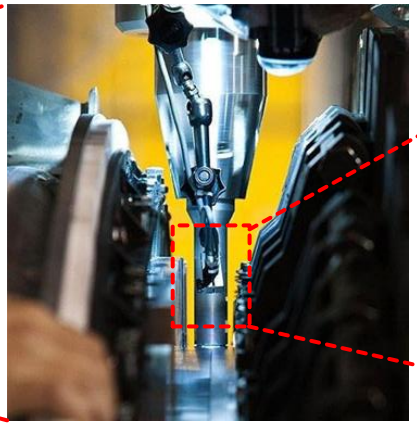
KITECH
한국생산기술연구원

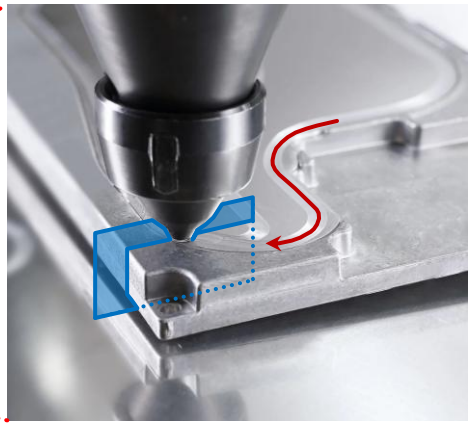
Research Objective – Prediction of FSW Quality

FSW Machine

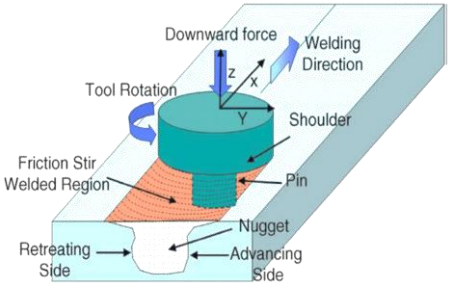
FSW Tool



FSW Joint

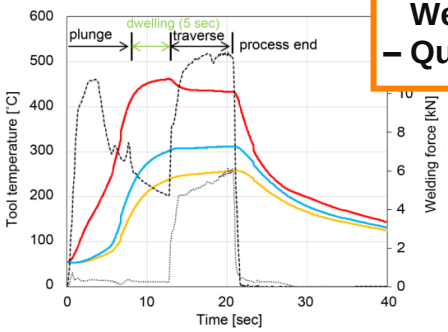


Process Parameters



- Tool rotation speed
- Feed rate
- Downward force

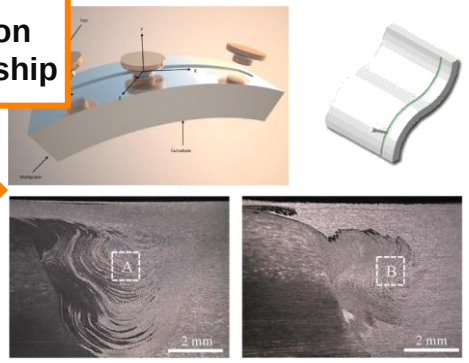
Tool Temperature



- Transient or stabilized temperature
- @ Probe, shoulder

Welding Condition – Quality Relationship

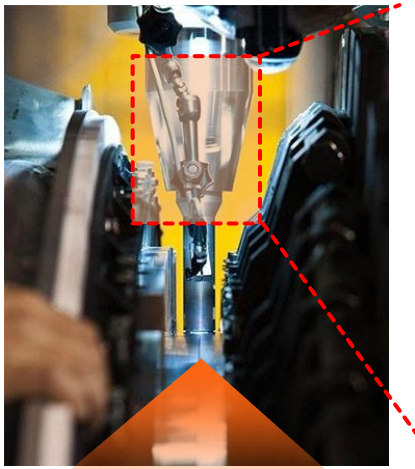
Welding Quality



- Tensile strength
- Internal microstructure (pore size, fraction)

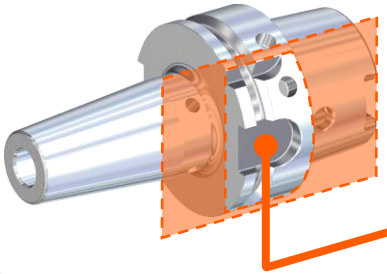
Approach

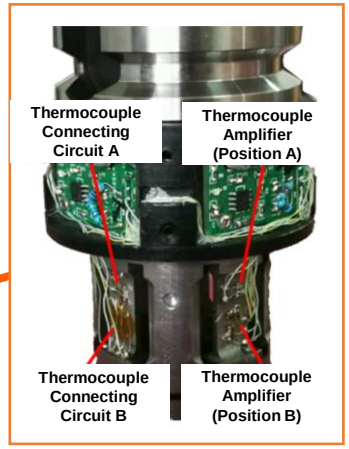
FSW Tool



Tool temperature measurement

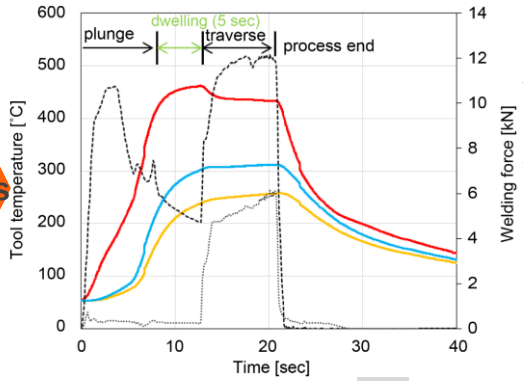
Smart Tool Holder





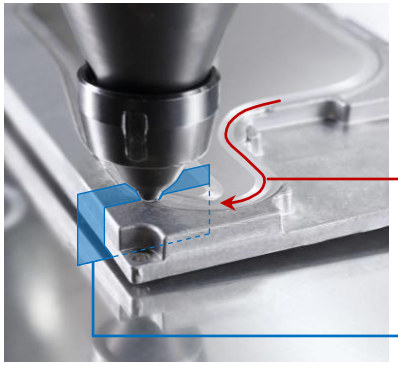
Wireless

Welding condition monitoring (Tool temperature)

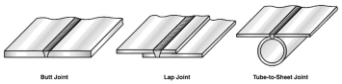


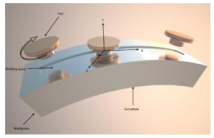
Welding cond.-Quality ML model

FSW Product

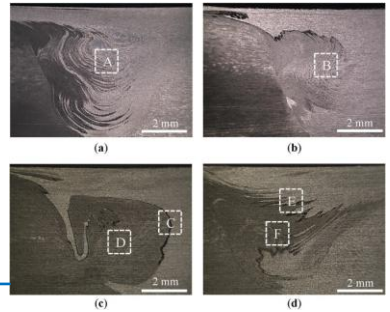


Welding geometry

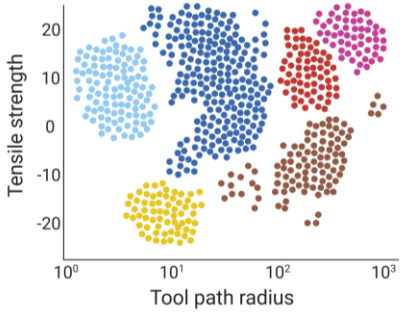




Microstructures



Welding quality

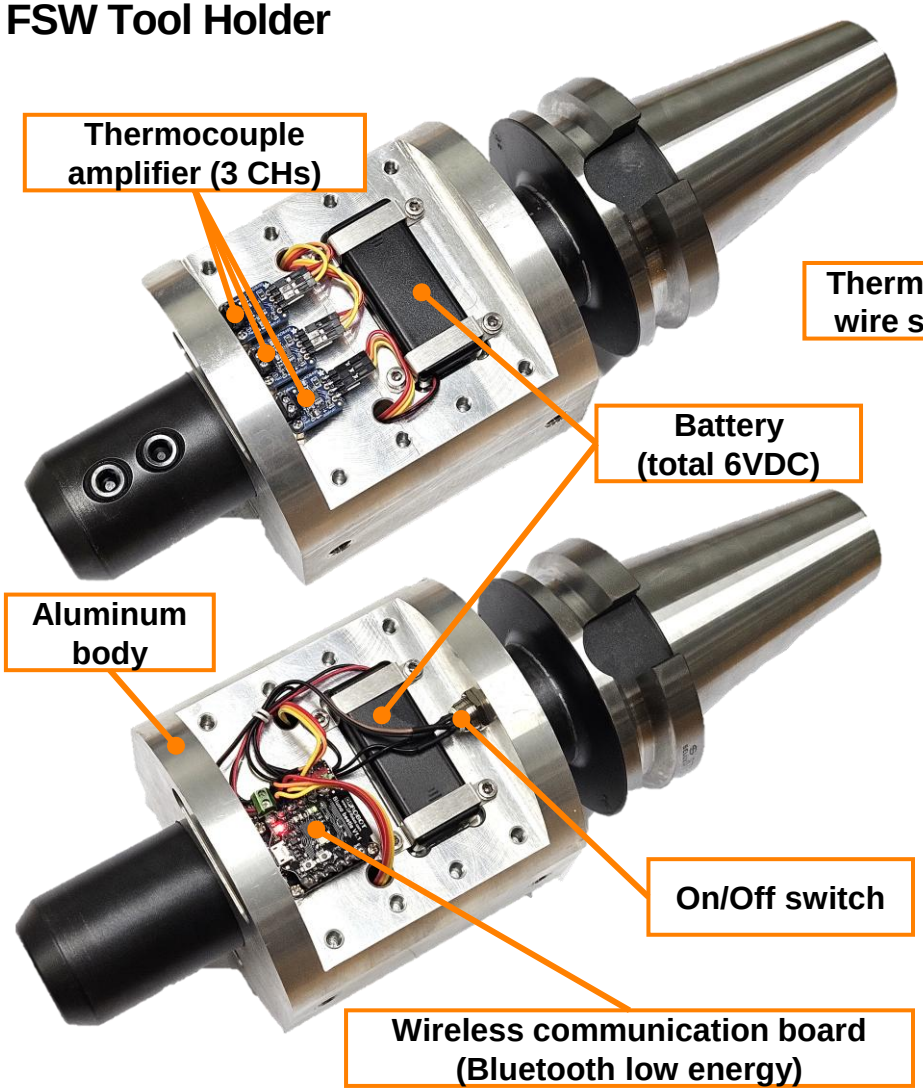


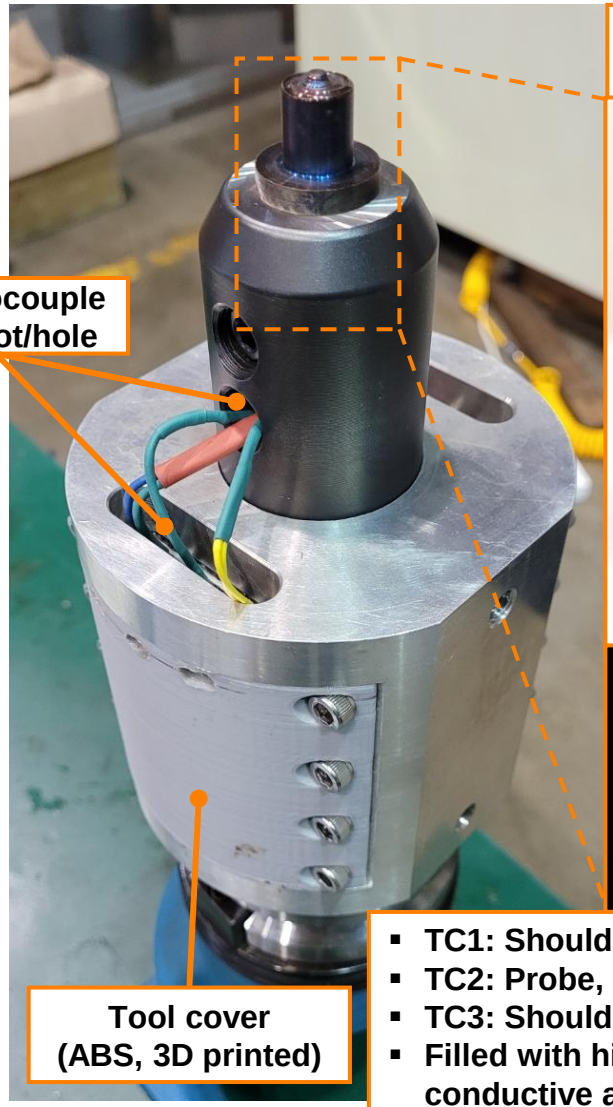
Physical Domain

Digital Domain

Wireless FSW Tool Temperature Measurement

FSW Tool Holder

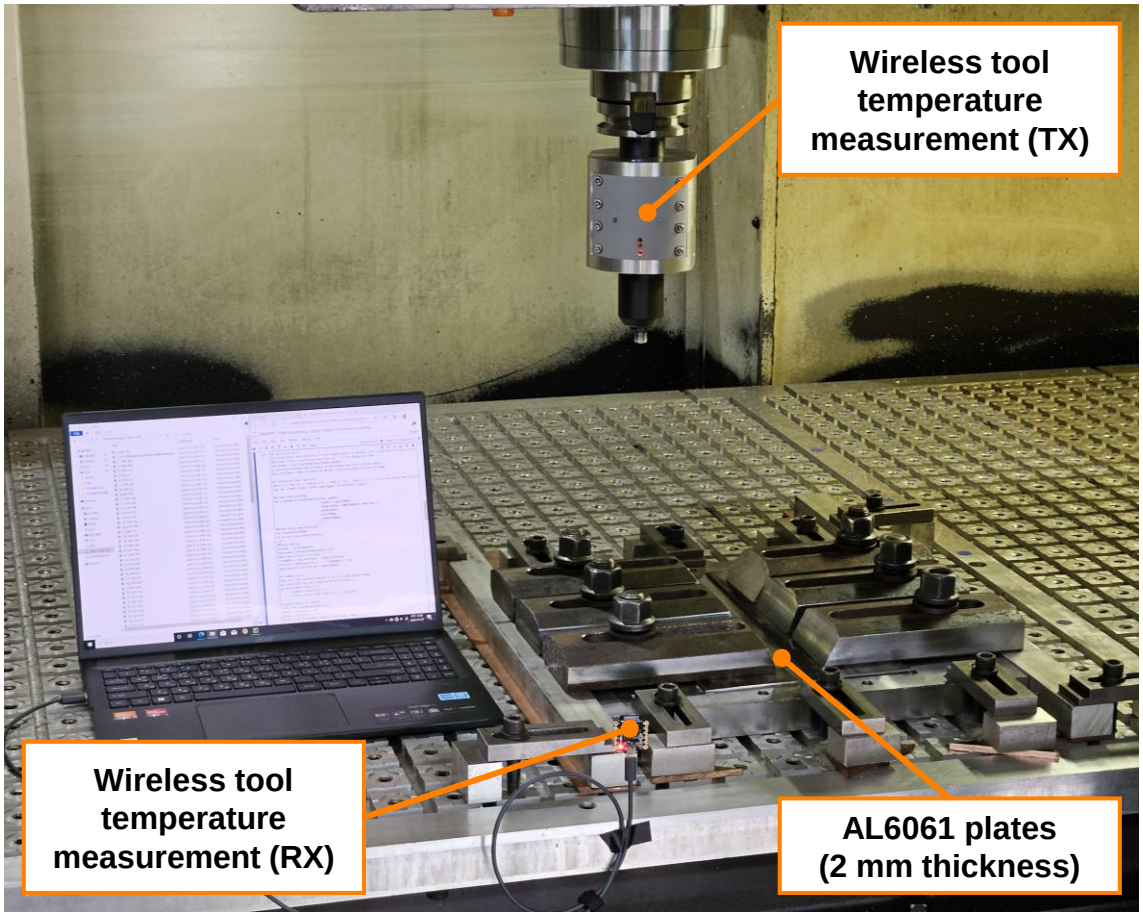


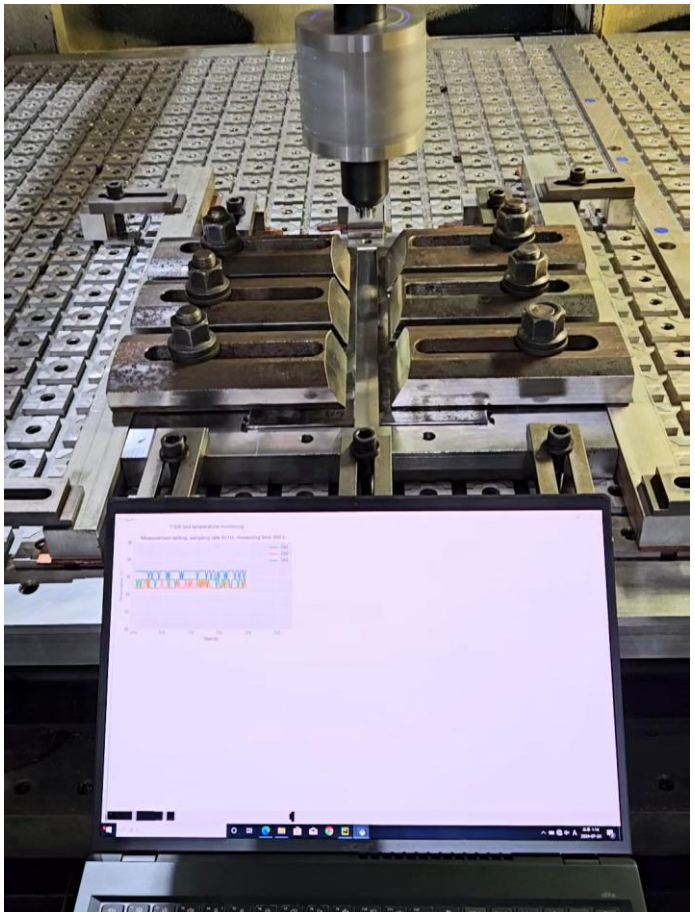


FSW tool w thermocouple

- TC1: Shoulder, dist. 5 mm
- TC2: Probe, dist. 2.5 mm
- TC3: Shoulder, dist. 1 mm
- Filled with highly thermal conductive adhesive

FSW Tool Temperature Measurement Setup



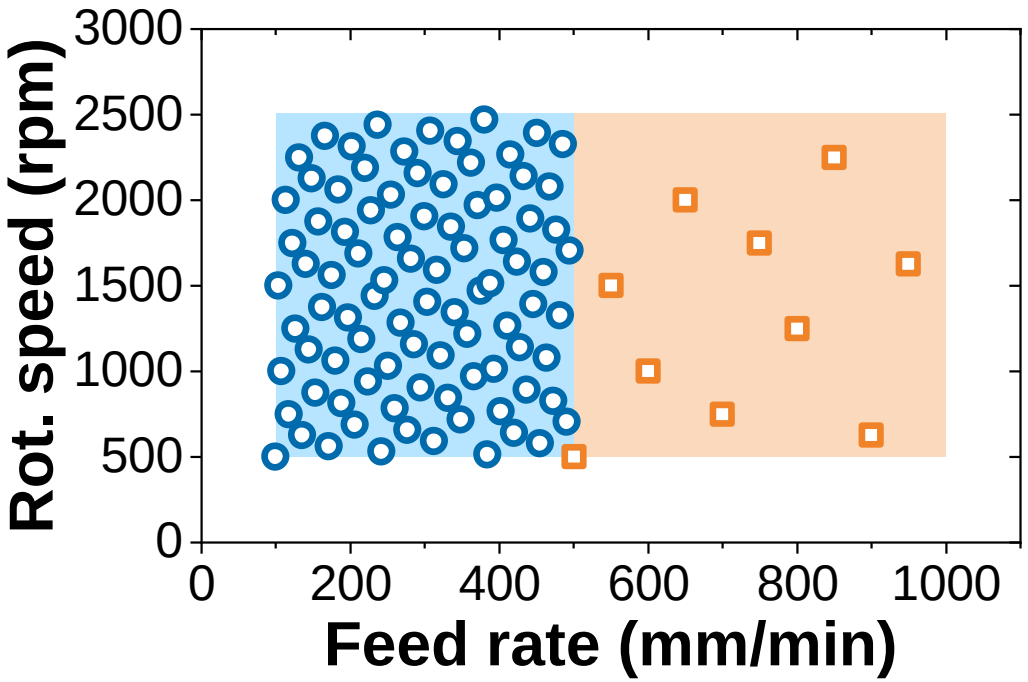


- Realtime tool temperature measurement
- Sampling rate 100 Hz/Ch, Operation time >4 hr
- No mechanical and electrical issue @ tool rotation speed ≤2500 rpm

FSW Temperature-Quality Data Preparation

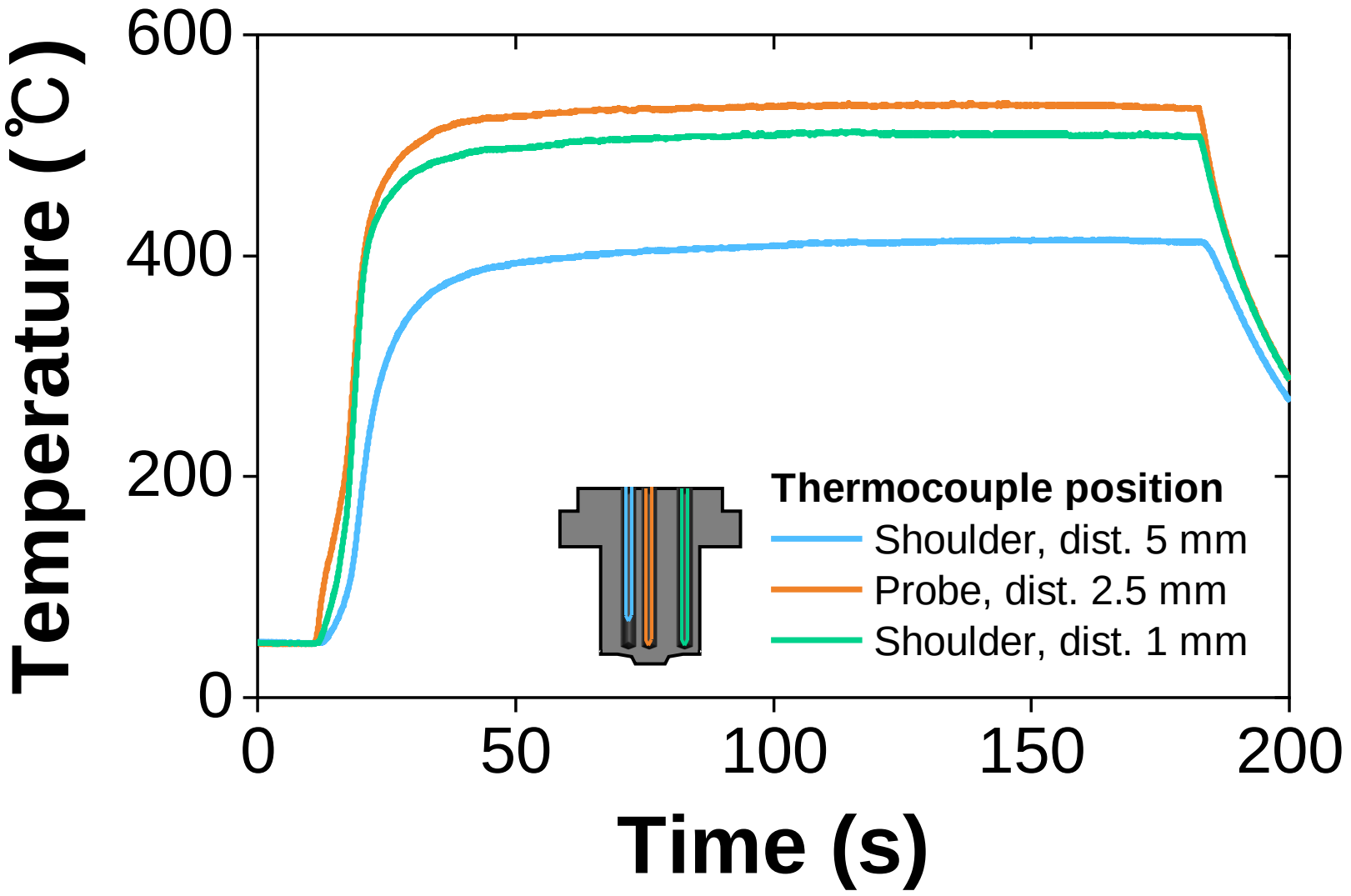
Design of Experiment (DoE)

- Process parameter: Tool rotation speed [500, 2500], Feed rate [100, 1000]
- DoE by *Hammersley Sequence Sampling (HSS), Total 100 samples
- Two HSS domain: Main / Extended
  - Main: 90 samples / Extended: 10 samples



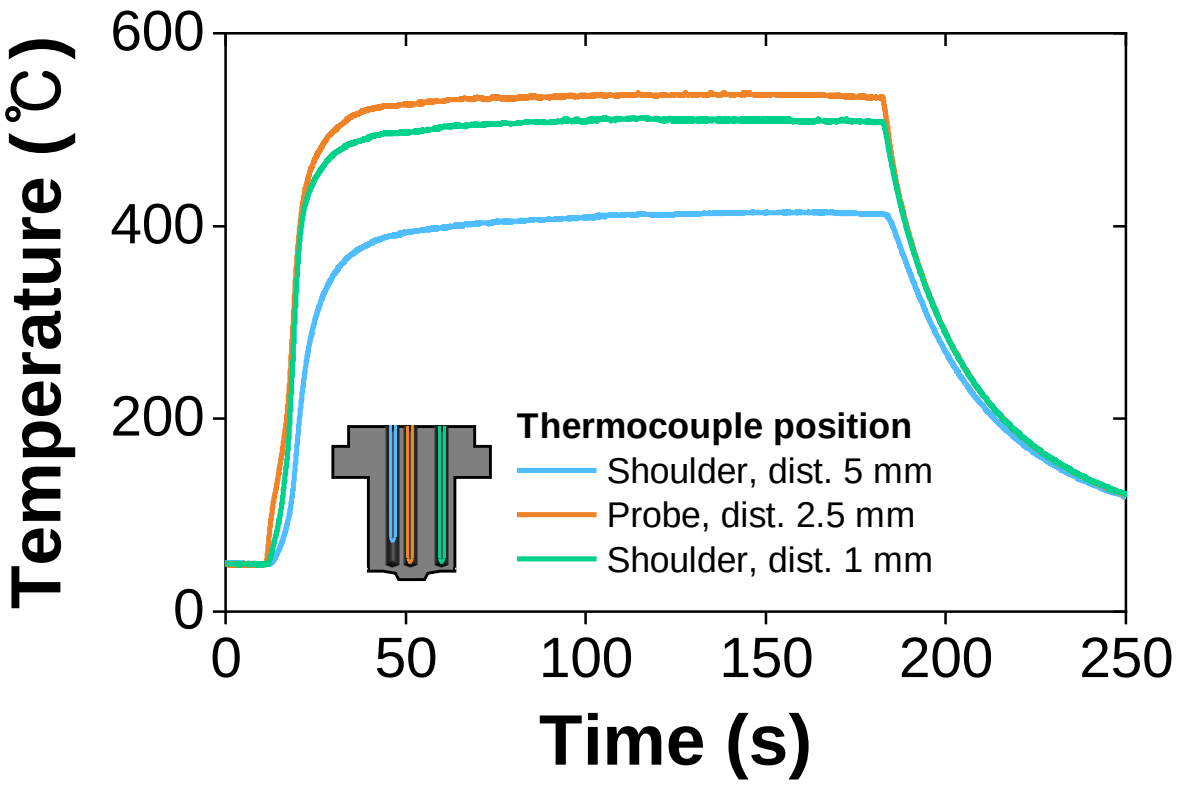
* Better DoE method for ML modeling than factorial or Latin hypercube sampling (LHS) due to minimized overlapping experimental conditions and low correlations between each experimental variable (Das S., Tesfamariam S., arXiv.2202.06416, 2022.)

Tool Temperature Profile at Different Positions

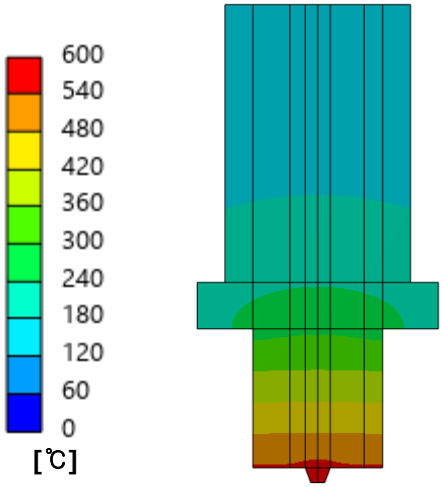


Tool Temperature Profile at Different Positions

Transient temperature profiles at different positions in FSW tool



FEM thermal analysis

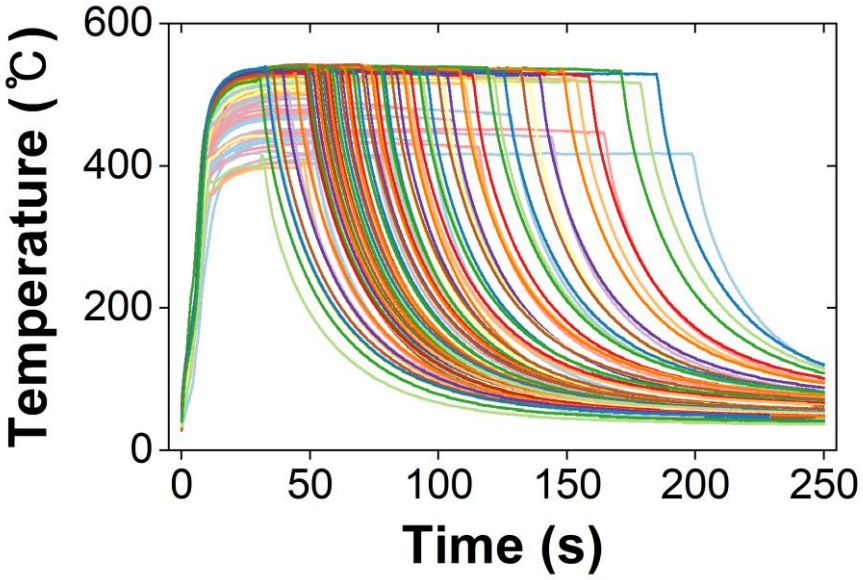


Position	Meas.	FEM
Shoulder, dist. 5 mm	414.7 ℃	414.5 ℃
Probe, dist. 2.5 mm	537.9 ℃	537.6 ℃
Shoulder, dist. 1 mm	512.5 ℃	512.2 ℃

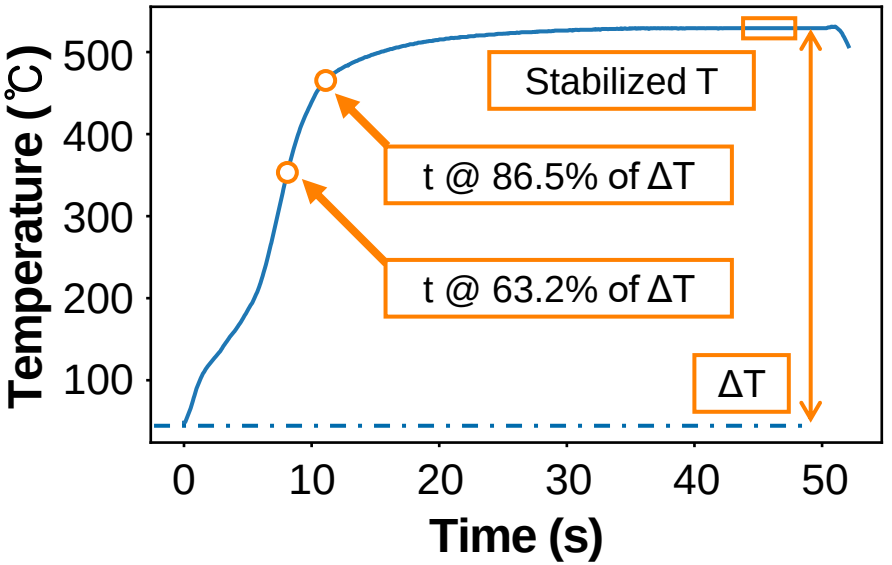
- Small difference to radial direction (measurement & FEM)
  ➔ Only temperature measurement at probe is sufficient
  (Probe, dist. 2,5 mm Vs. Shoulder, dist. 1 mm ➔ Almost same depth)

FSW Temperature-Quality Data Preparation

Probe temperature at 100 different condition



Feature extraction (e.g., 1578 rpm, 460 mm/min)

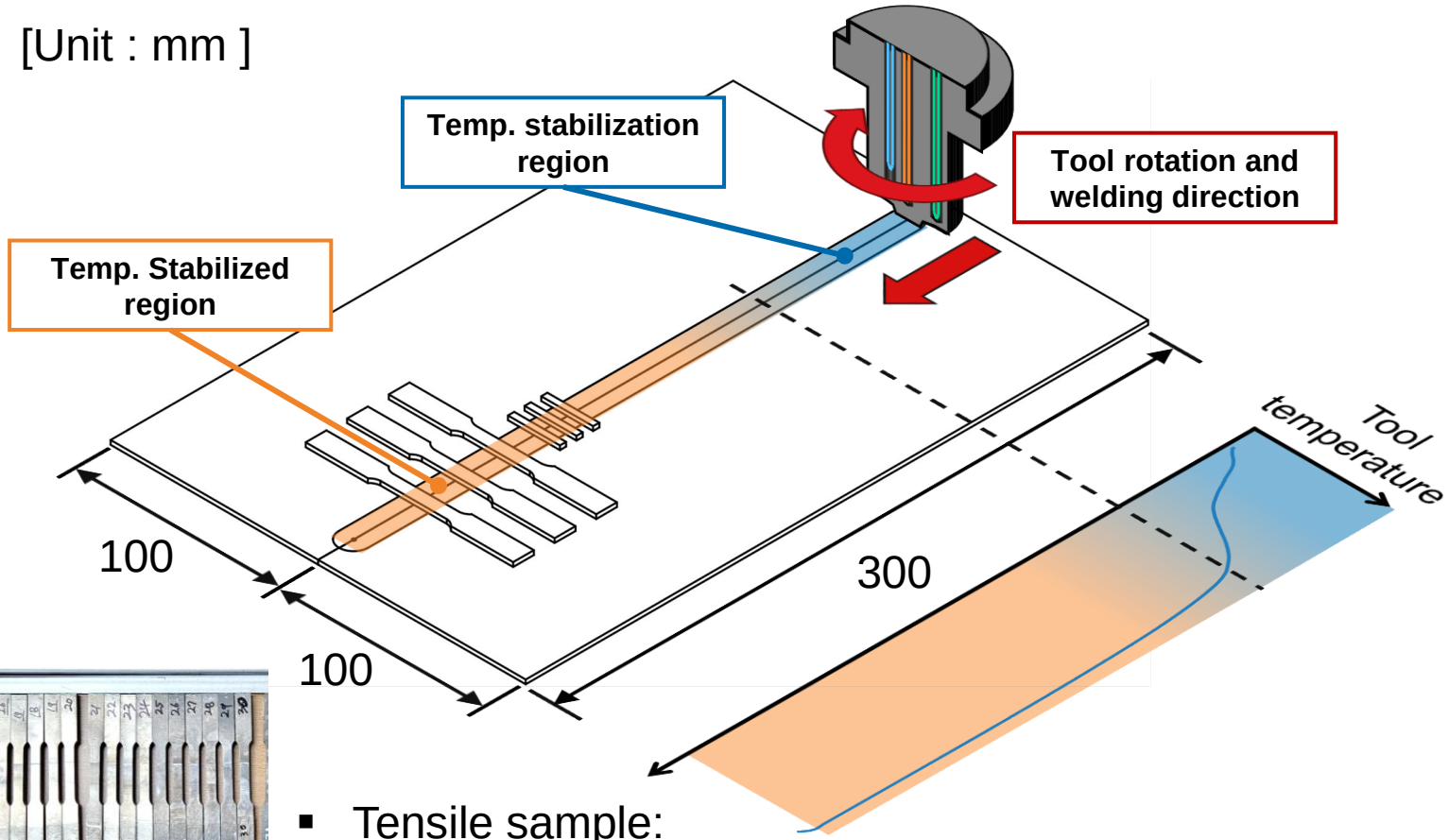


- Feature extraction by geometrical feature of the temperature profiles
- 1. Temperature after stabilization
- 2. Time at 63.2% of ΔT (~ 1 τ; Time constant)
- 3. Time at 86.5% of ΔT (~ 2 τ; Time constant)

- More features will be determined.

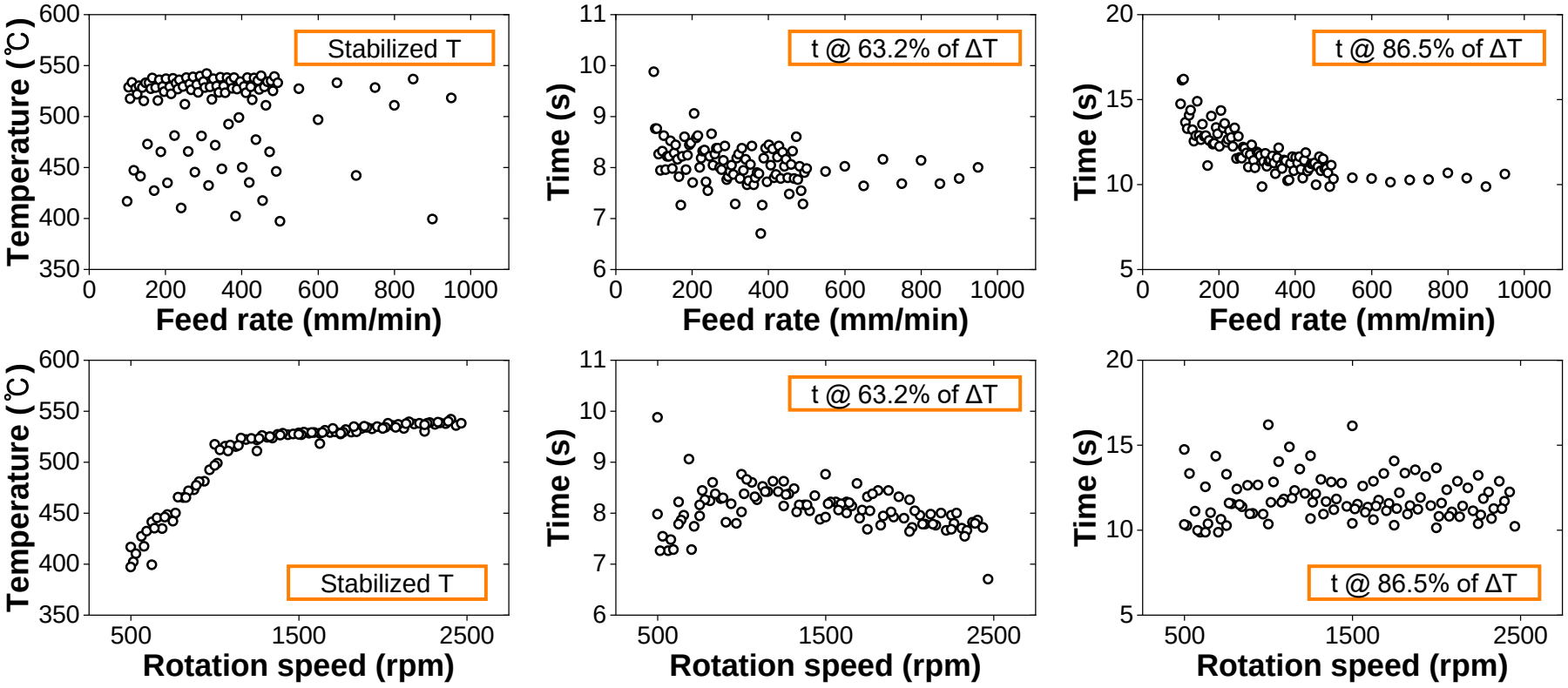
FSW Quality Measurement Sample Preparation

[Unit : mm]

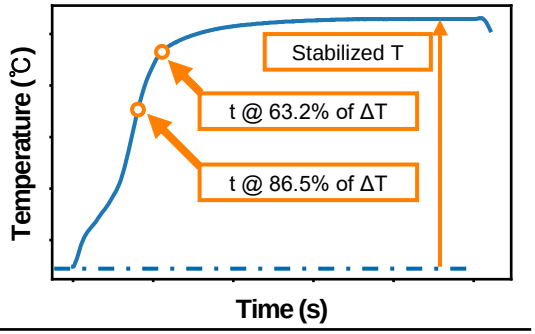


- Tensile sample:
  ASTM E8/E8M-13a, 3 sample/condition
- Sample for microstructure analysis:
  5×26×2 mm, 3 sample/condition
- All samples were from the temp stabilized region.

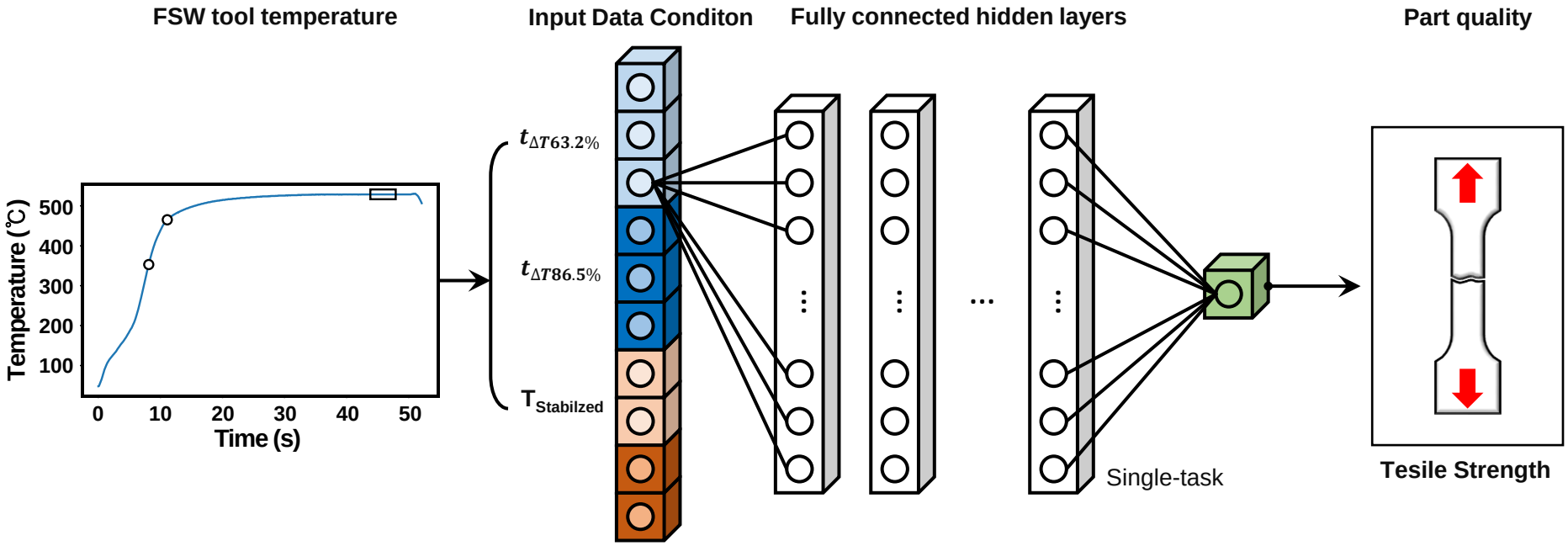
FSW Process Parameter – Feature Correlation



- Strong correlation between
  a) Tool rotation speed – Stabilization temperature
  b) Feed rate – Time at 63.2% of ΔT
  c) Feed rate – Time at 86.5% of ΔT



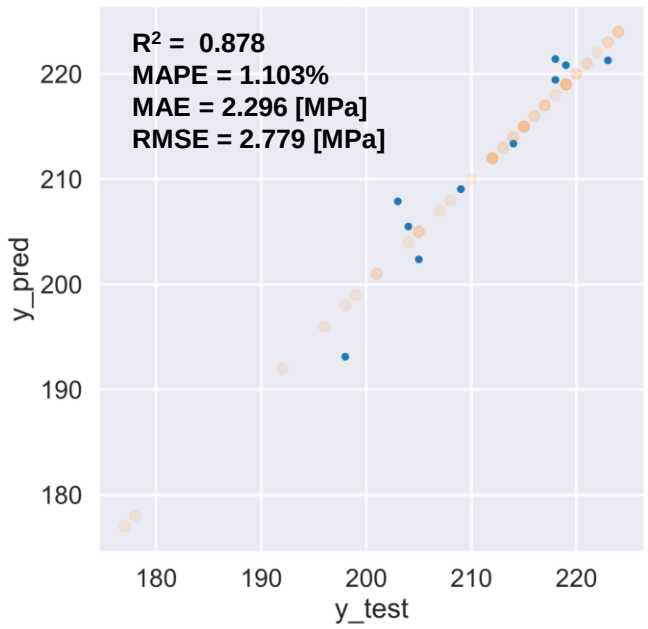
Tool Temperature – Welding Strength ML Model

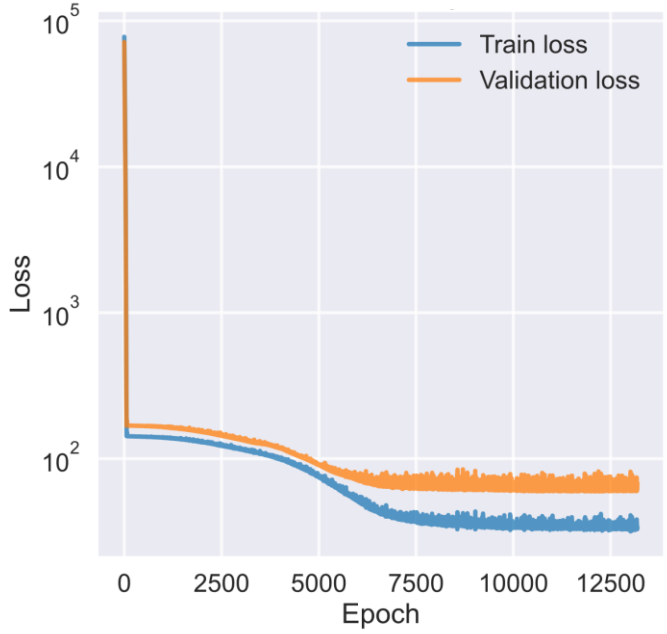


Hyperparameter	Range	Optimized
# of hidden layers	1, 2, 3	**3**
# of neuron per a hidden layer	8, 16, 32	**16**
Learning rate	0.1, 0.01, 0.001	**0.01**
Activation	ReLU, gelu, elu, swish, softplus	**elu**
Initializer	glorot_normal, glorot_uniform, he_normal, he_uniform, lecun_normal, lecun_uniform	**Lecun_uniform**
Optimizer	Adam, Adadelta, Adamax	**Adamax**

* Hyperparameter optimization (HPO) by Hyperband algorithm with Tree-structured Parzen Estimator (TPE) and pruning.
* Early stopping and restoration of the best model were applied for main training after HPO

Prediction Performance of ML Model



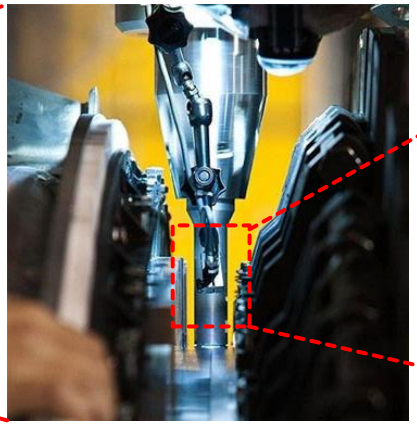


Measured Tensile Strength (MPa)	Predicted Tensile Strength (MPa)	Error (%)	Measured Tensile Strength (MPa)	Predicted Tensile Strength (MPa)	Error (%)
198	193.12	**2.46**	214	213.37	**0.29**
203	207.89	**2.41**	223	221.29	**0.77**
205	202.37	**1.28**	218	221.42	**1.57**
209	209.05	**0.02**	219	220.83	**0.84**
204	205.5	**0.73**	218	221.42	**1.57**

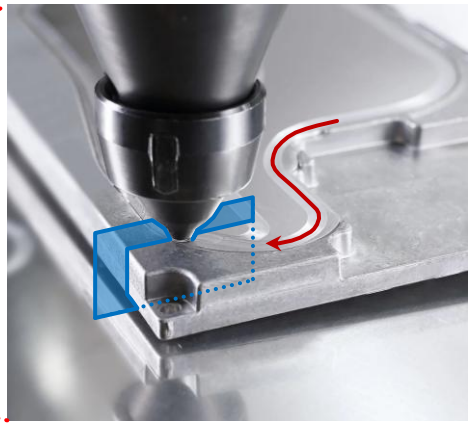
Research Objective – XAI Analysis

FSW Machine

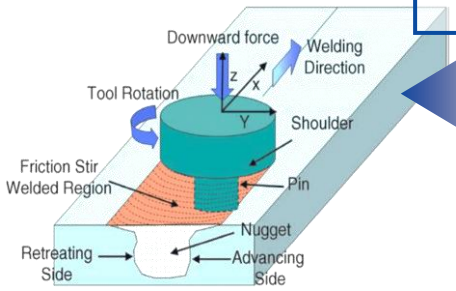
FSW Tool



FSW Joint

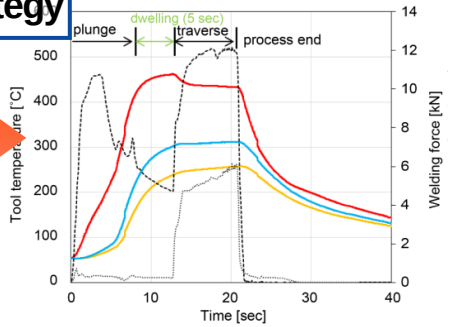


Process Parameters

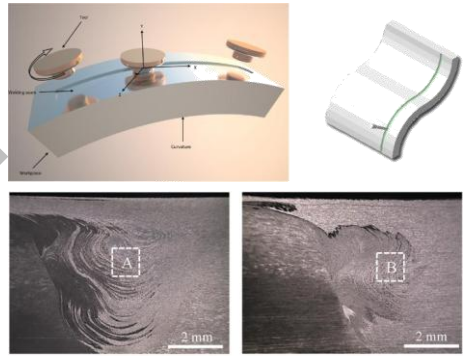


- **FSW process control strategy**

Tool Temperature



Welding Quality



- Influential features (Time, temperature)
  - ➔ **Specific quality-targeted monitoring window, ML model improvement**

XAI

Black box (Opaque characteristics)

Conclusions

- The developed FSW tool module was capable of measuring tool temperature to accurately predict the ultimate strength in FSW.
- Analysis of the measured tool temperature profiles presented that rotational speed had a greater influence on temperature than feed rate.
- The tool temperature profile features were used as input feature for the ANN to predict ultimate tensile strength.
- Overall prediction performance of the ANN model was ≥98% accuracy (1-MAPE).

Acknowledgements

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KITECH-AU Joint International Cooperation Research
Weld Joint Analysis for Quality Prediction of Friction Stir Welding
(PI: Chanho Lee)

KITECH-Auburn Univ. Manufacturing Technology Innovation Center
(KAMTIC)

디엔엠항공
Distribution and Manufacturing for Aerospace

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