Metallurgical study of Japanese swords by using pulsed neutron imaging methods

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OUTLINE

- Objectives
- Measured Japanese swords, spears and naginata
- Information obtained by using Bragg edge transmission
- Crystallite size distributions of Japanese swords
- Characteristics of the Bizen swords
- Swords with different type crystallite size distributions
- Summary

OBJECTIVES

So far the Japanese swords have been appreciated by viewing the surface. (wave pattern, fine structure of the surface iron and so on)

However, metallurgical characteristics over a wide area of inner iron is useful information to consider the sword feature.

Invasive methods have been used so far. However, it was difficult to cover large area to see the change of the characteristics continuously and usually difficult to break cultural heritages.

Bragg edge transmission is a unique method to obtain metallurgical information over the wide area of the sword continuously.

By using this method and CT (additionally, muon), we intend to

→ investigate metallurgical characteristics inside a sword, and then consider the structure/making process,

→ elucidate difference and similarity depending on production places and ages,

→ discuss propagation of sword making techniques.

Japanese swords research group: KATANA Project

(Mariage of neutron noninvasive research group and invasive research group)

KATANA (Knowledge Acquisition on Tatara Artifacts by Neutron Analysis) Project

Representative：Y. Kiyanagi
（Emeritus Prof.
Hokkaido University)

Shimane University
S. Morito, Pham H. Anh
T. Ohba (Emeritus Prof.)

Invasive research

Kumamoto University
Y. Mine

Hokkaido
University
H. Sato

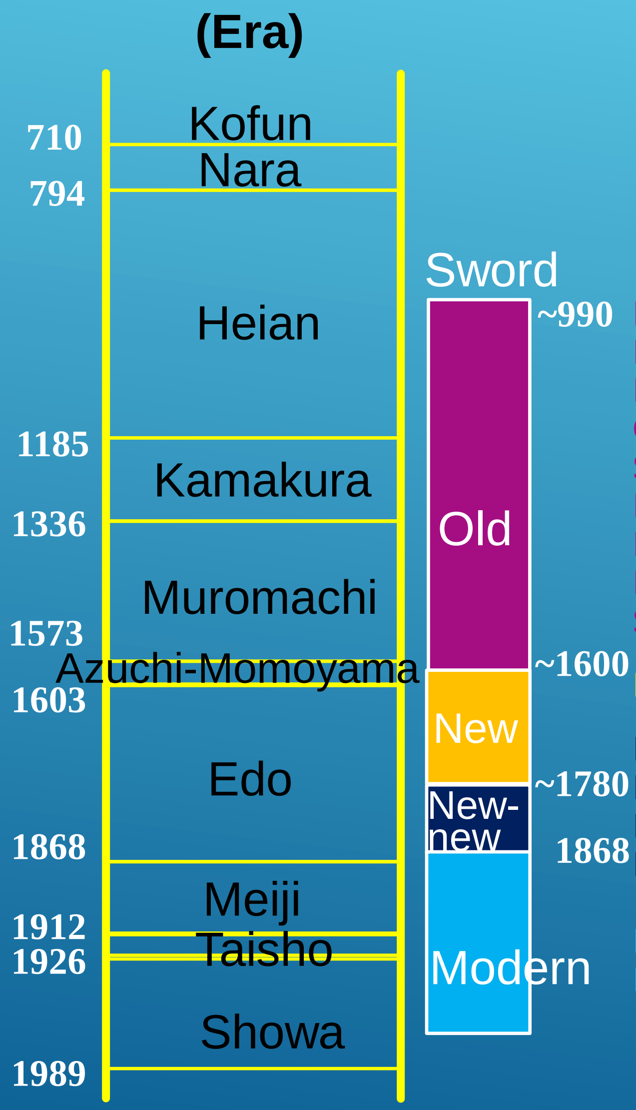
J-PARC K. Oikawa, T. Shinohara,
T. Kai, S. Harjo
CROSS   Y. Matsumoto

Kyushu
University
K. Watanabe

Non-invasive research

Measured
Japanese swords, spears and naginata

Swords, Spears and Naginata so far Measured (Swordsmith and Place)

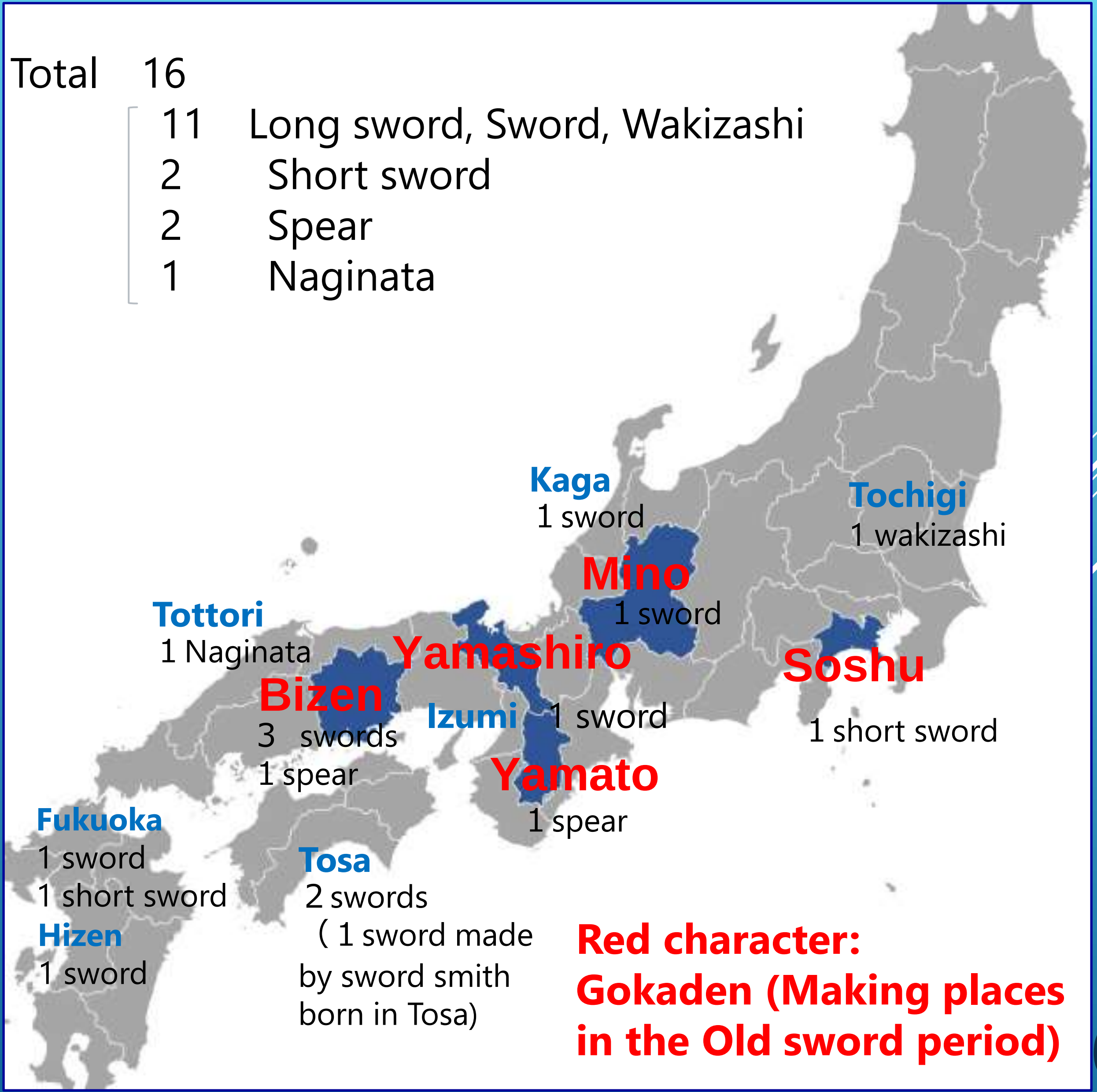


Norimitsu (Wakizashi: Bizen)
Morikage (Bizen)
Noritsuna (Bizen)
Osahune Koremitsu (Spear: Bizen)
Sukemasa (Izumi)
Hiromasa (Short: Soshu)
Kanehusa Masaszane (Spear: Yamato)
Kanesada (Mino)
Sa Masayoshi (Short: Chikuzen)

Fujiwara Tadahiro (Hizen)

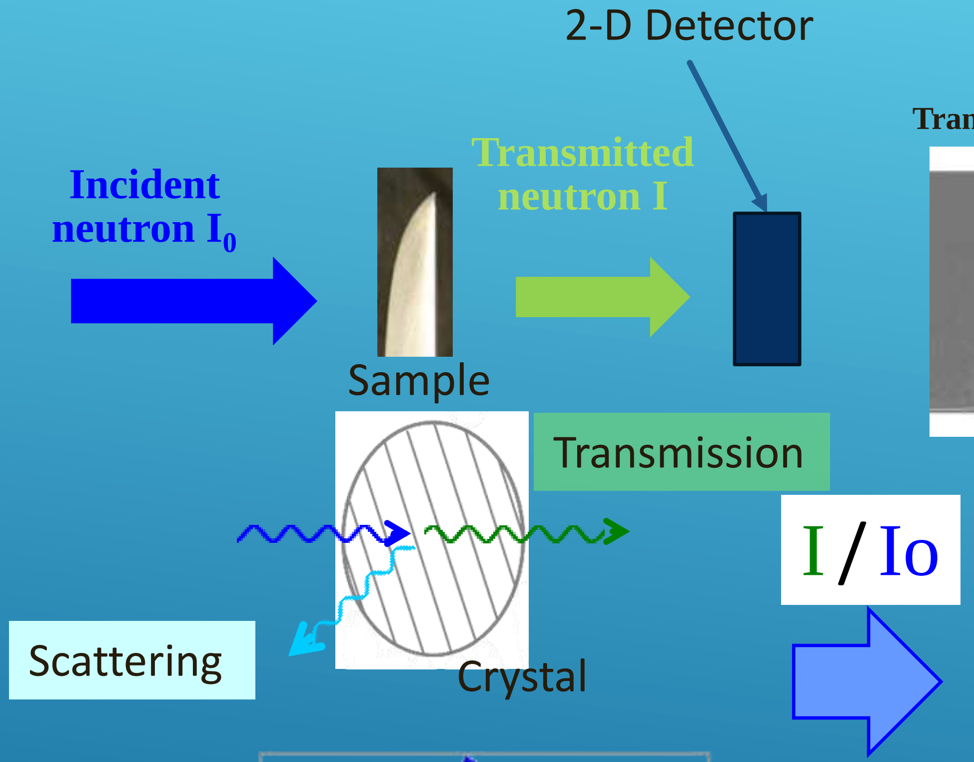
Kashu Kiyomitsu (Kaga)
Mutsunokami Yoshiyuki (Tosa)
Nankai Taro Tomotaka (Born in Tosa)
Kenryushi Toshiyuki (Naginata: Tottori)

Hosokawa Masanori (Wakizasi:Tochigi)
Masamitsu (Fukuoka)



Information obtained by neutron Bragg edge transmission

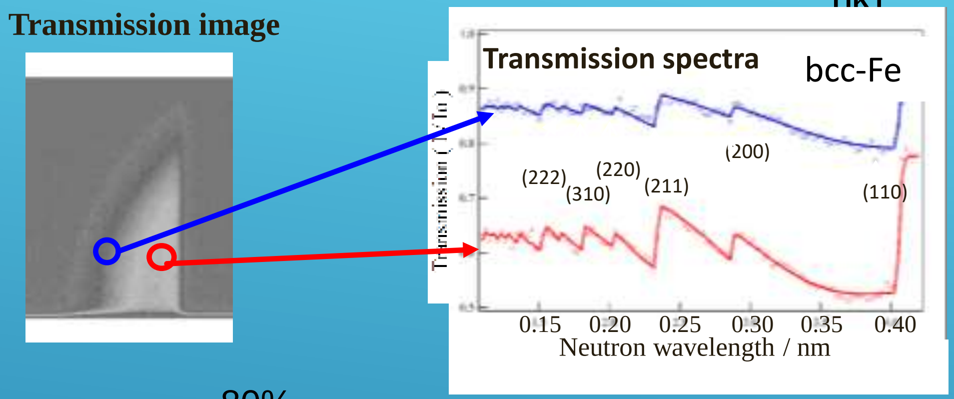
Principle of Neutron Bragg Edge Transmission (BET)

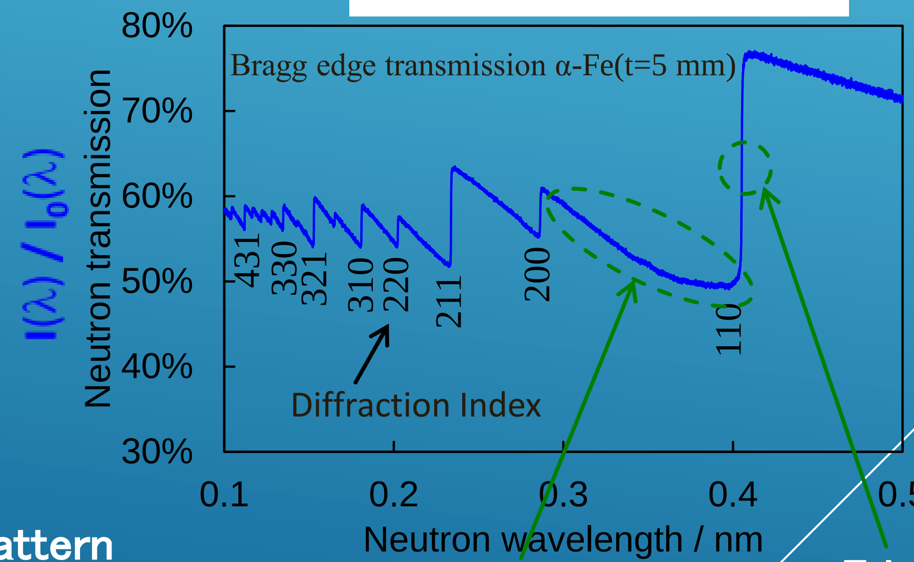


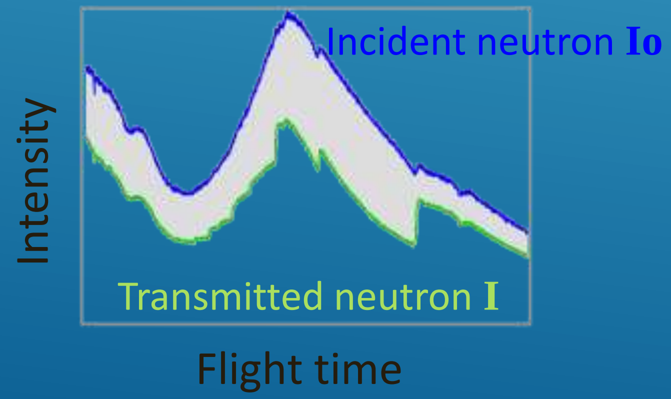
Bragg edge

Bragg law

$$\lambda = 2d_{hkl} \times \sin\theta$$







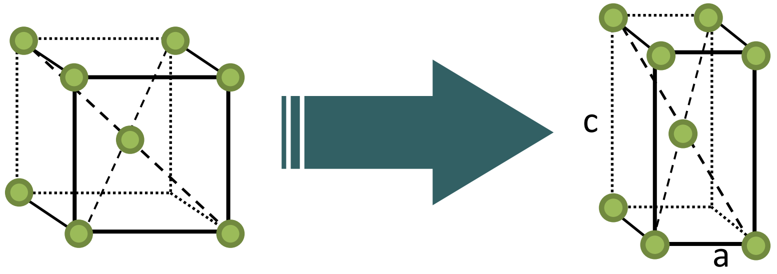
Edge pattern (Position & Height)
- Crystal structure
- Crystal phase

Shape & Transmission
- Texture (Orientation)
- Crystallite size

Edge
- Lattice plane spacing
- Strain (Quenching)

1. Quenching at a edge side （Martensite）⇐ Bragg edge broadening

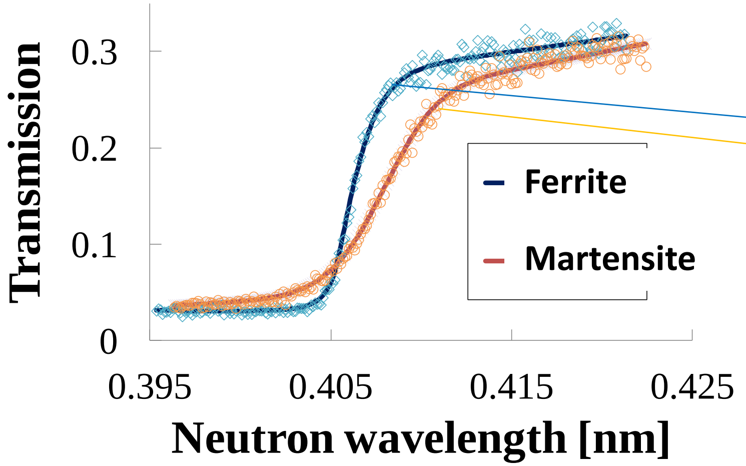
Enlarging C axis --→ Gentle edge slope

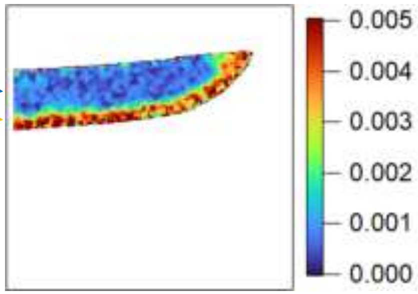


Ferrite: BCC

Martensite: BCT

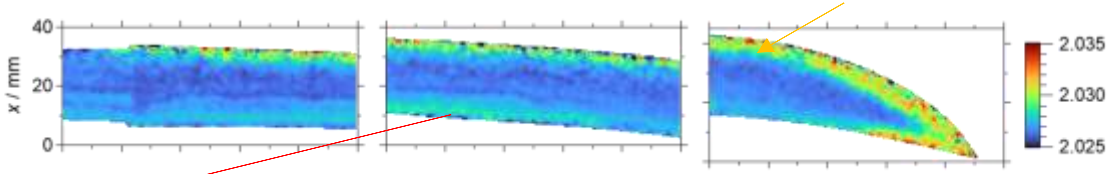
Bragg edge broadening





2. Strain ⇐ Lattice plane spacing

Quenching
(Martensite)



Lattice plane spacing

The sword bents toward the backside by quenching
(Compression at backside)
→ Enlarging the lattice plane spacing in thickness direction

Before quenching

After quenching

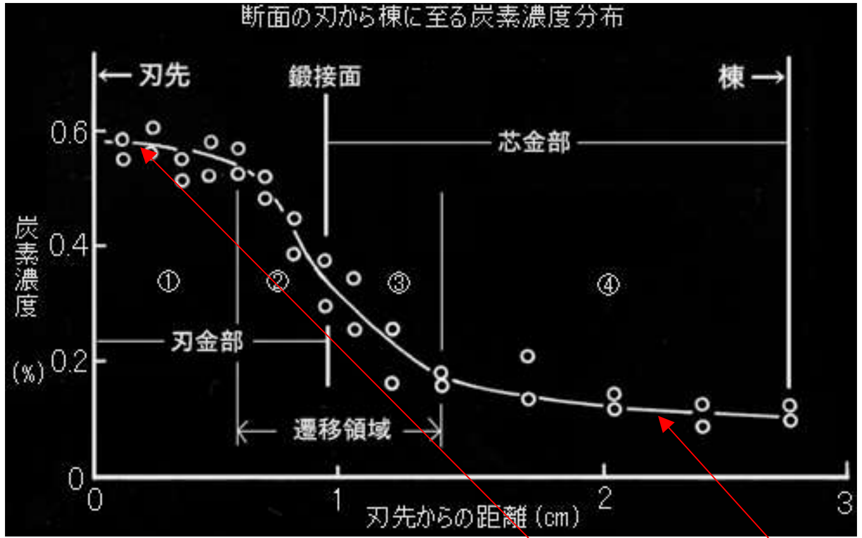
Compression

3. Carbon content ⇦ Crystallite size

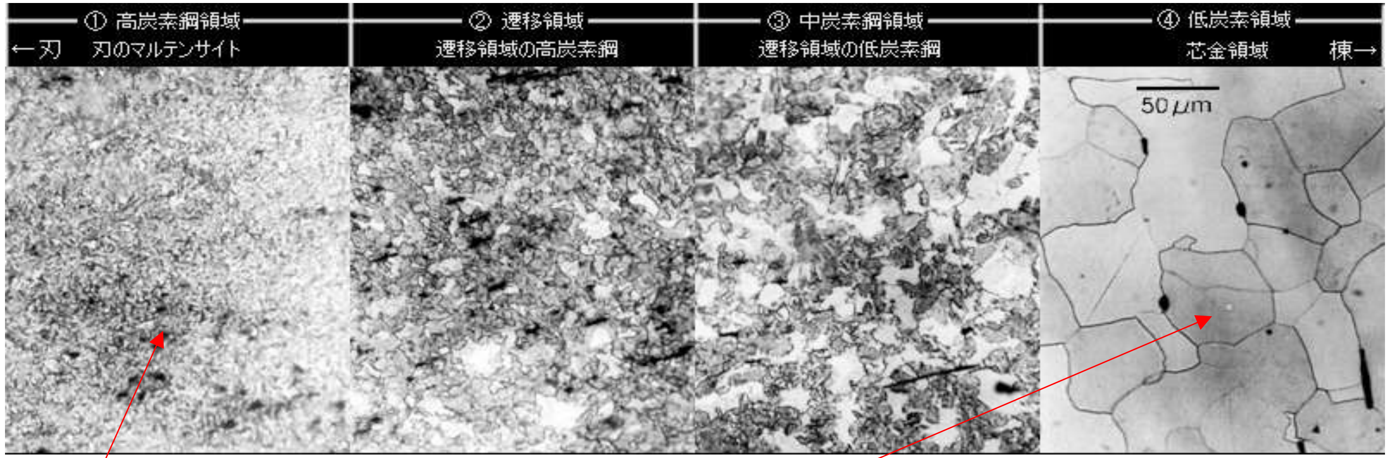
Carbon content decreases from tip(~0.6%) to backside (~0.1%) and particle size become larger.

M. Kitada, Fine structure of Japanese swords in Muromachi era, Uchida Rokakuho (2008).

Carbon content from edge to back side



Particle size

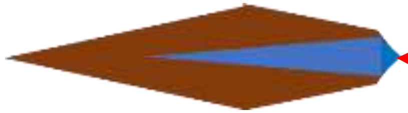


Edge side (Martensite)

Transition area (High carbon)

Transition area (Medium carbon)

Core iron (Low carbon)



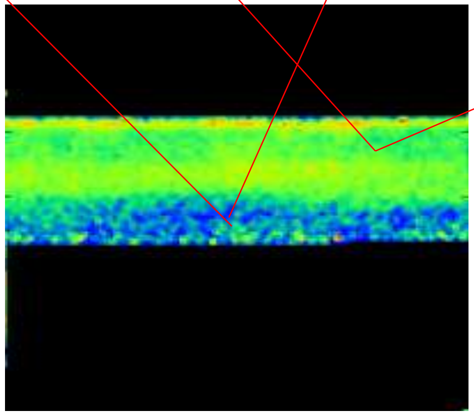
Core iron

Surface iron

Crystallite size

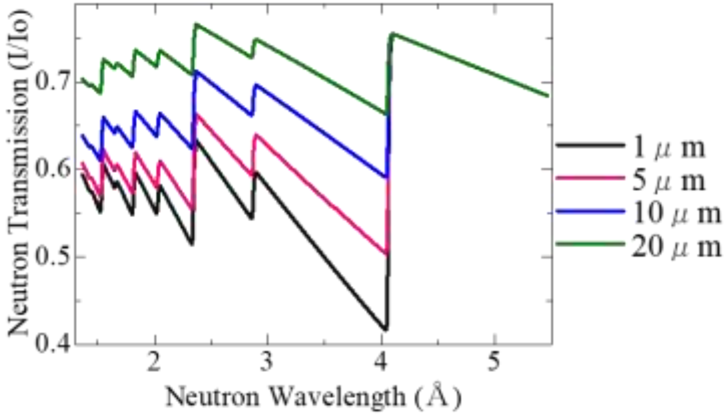
Large

Small



Backside

Edge side



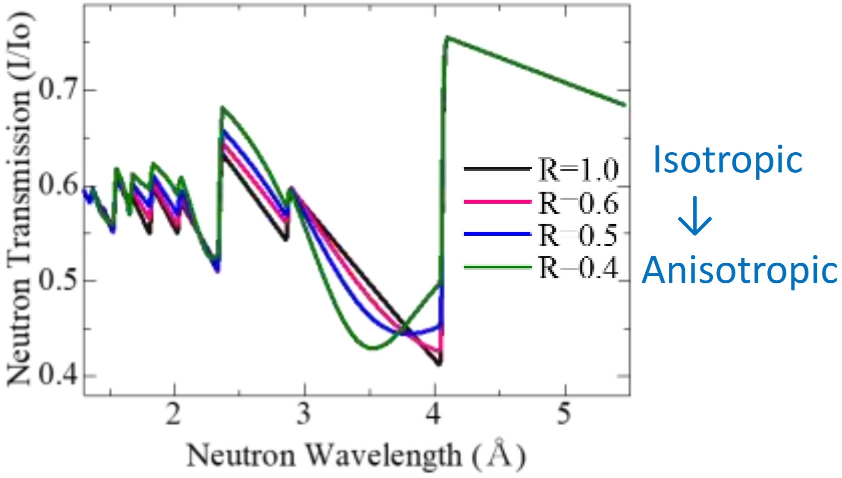
Larger crystallite size gives higher transmission.

4. Forging process ⇐ Texture(Orientation)

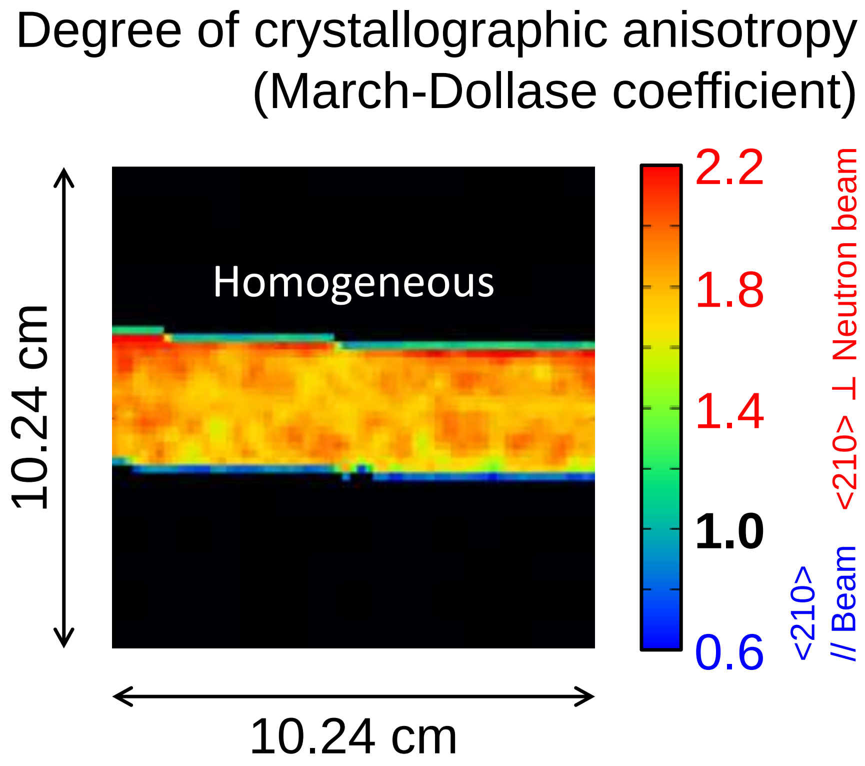
Crystallites align along a rolling direction.

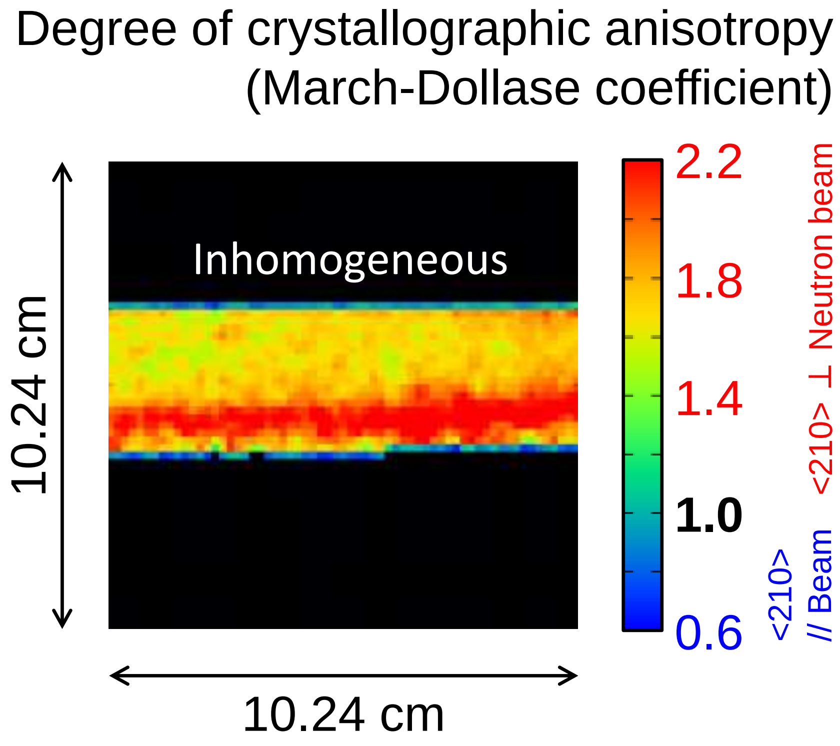
Forging process and its strength may affect the texture.

Detailed relation is not yet clear.



Examples of texture

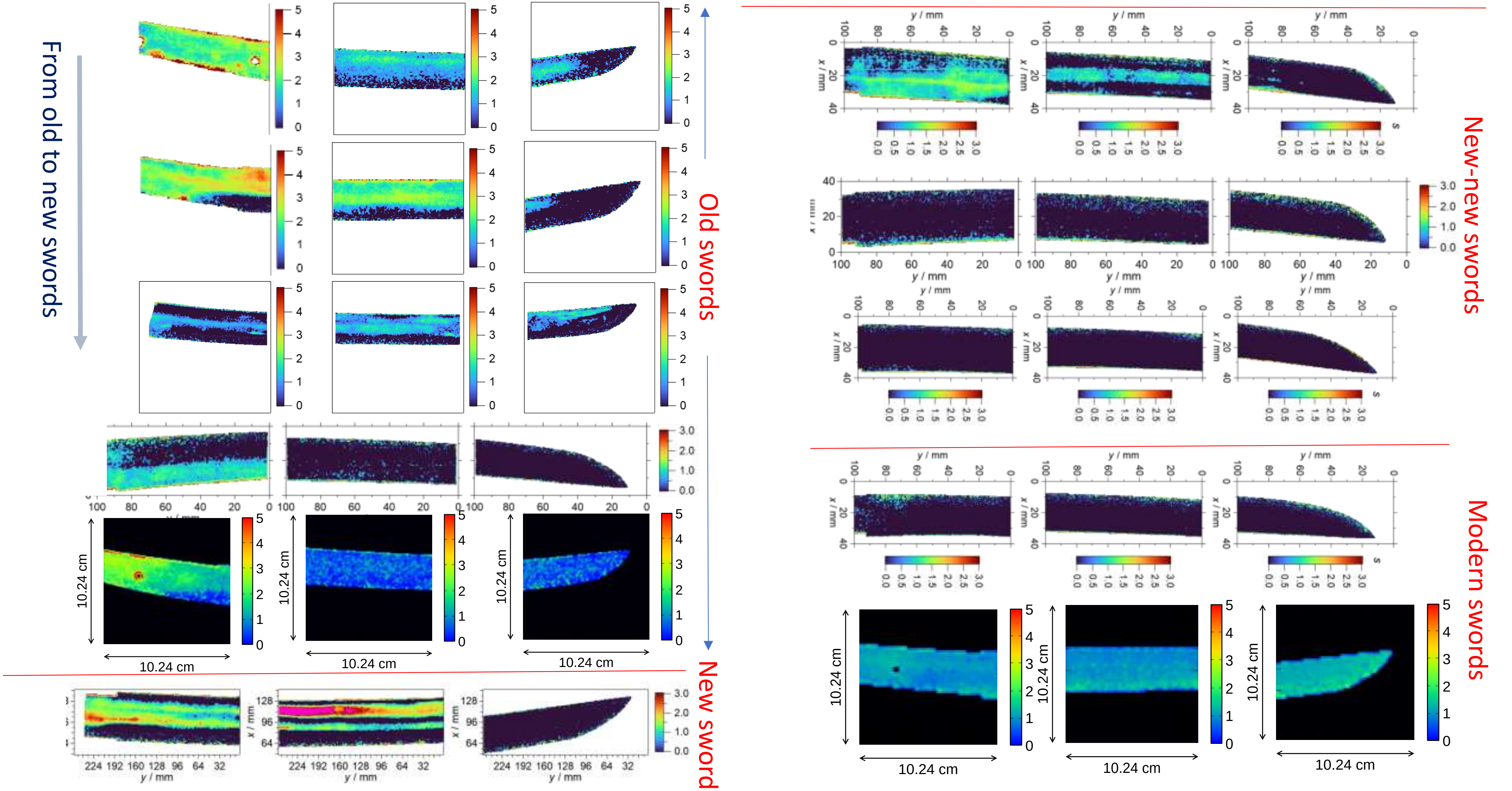




Crystallite size distributions of Japanese swords

Crystallite size distribution shows peculiar feature.
Here, the distributions are shown and they are categorized according to their patterns.

Crystallite size (μm) distributions for various swords at different ages and places



Characteristics of the Bizen swords

(References)

Noritsuna Bragg edge data

H Sato, Y Kiyanagi, K Oikawa, et al., Materials Research Proceedings 15, 214-220 (2020).

Norimitsu Bragg edge data

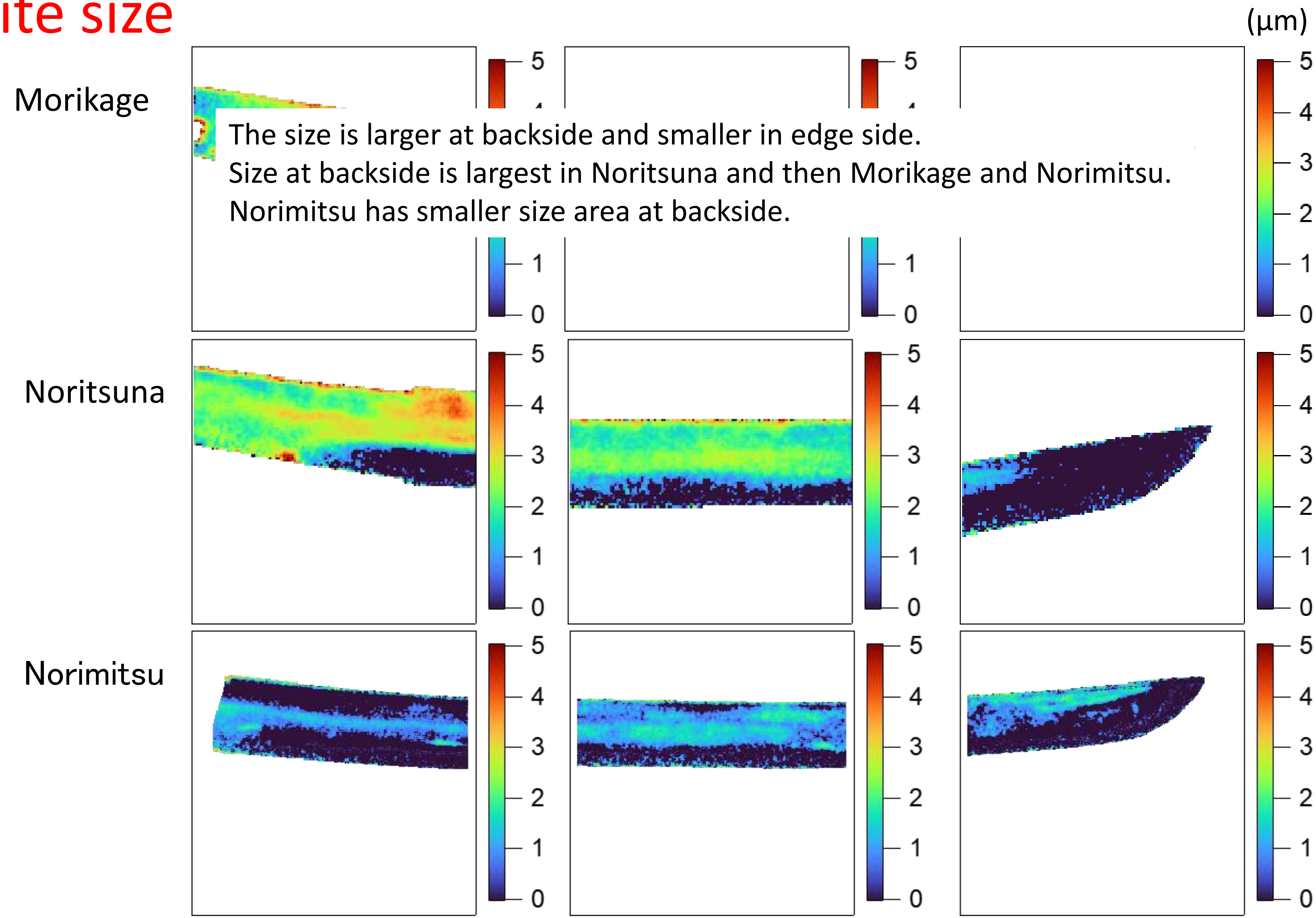
Norimitsu Bragg edge and CT data

K Oikawa, Y Matsumoto, K Watanabe, H Sato, J D Parker, T Shinohara, Y Kiyanagi: Energy-resolved Neutron Imaging Study of a Japanese Sword Signed by Bishu Osafune Norimitsu, submitted to Scientific Report.

Morikage CT

Y Matsumoto, K Watanabe, K Ohmae, et al., Materials Research Proceedings, 15, 221-226 (2020).

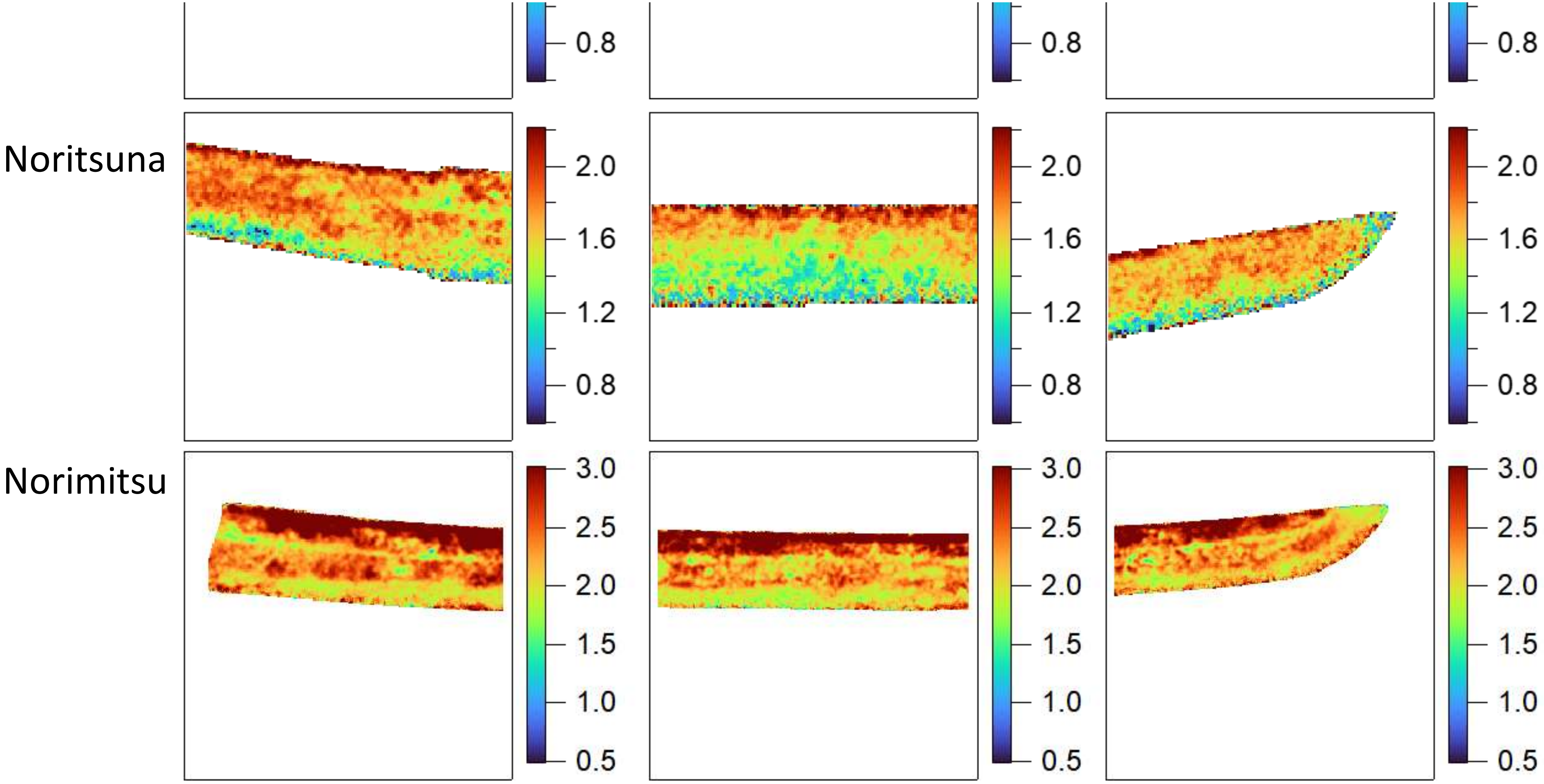
Crystallite size



The size is larger at backside and smaller in edge side.
Size at backside is largest in Noritsuna and then Morikage and Norimitsu.
Norimitsu has smaller size area at backside.

Texture

The strongest texture appears at backside of Norimitsu (maximum range is 3.0) and texture becomes a little bit weaker at backsides of Noritsuna (maximum range is 2.0). Morikage has rather strong texture over the whole sword.



Lattice plane spacing (110)

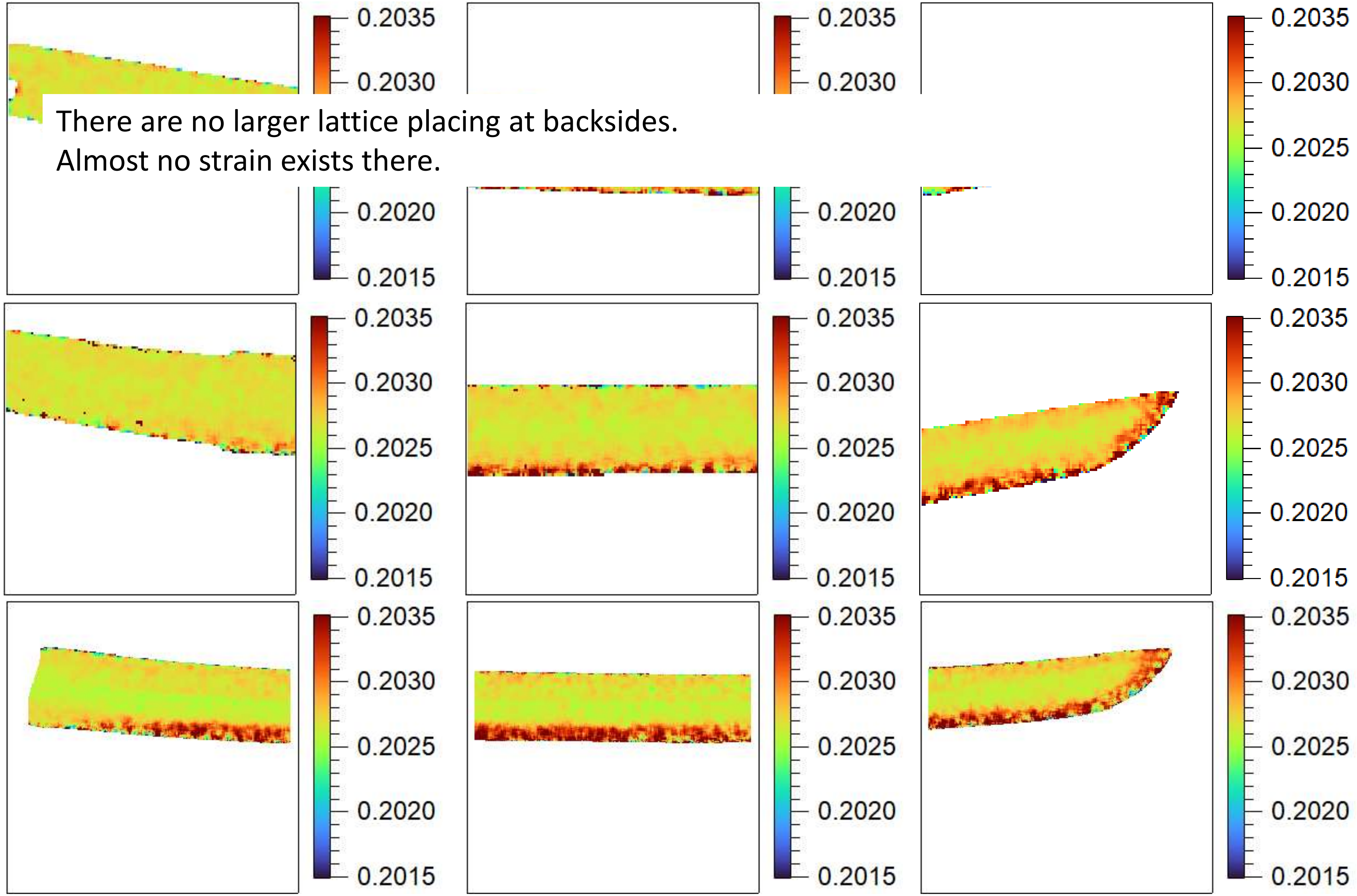
0.2027 nm

(nm)

Morikage

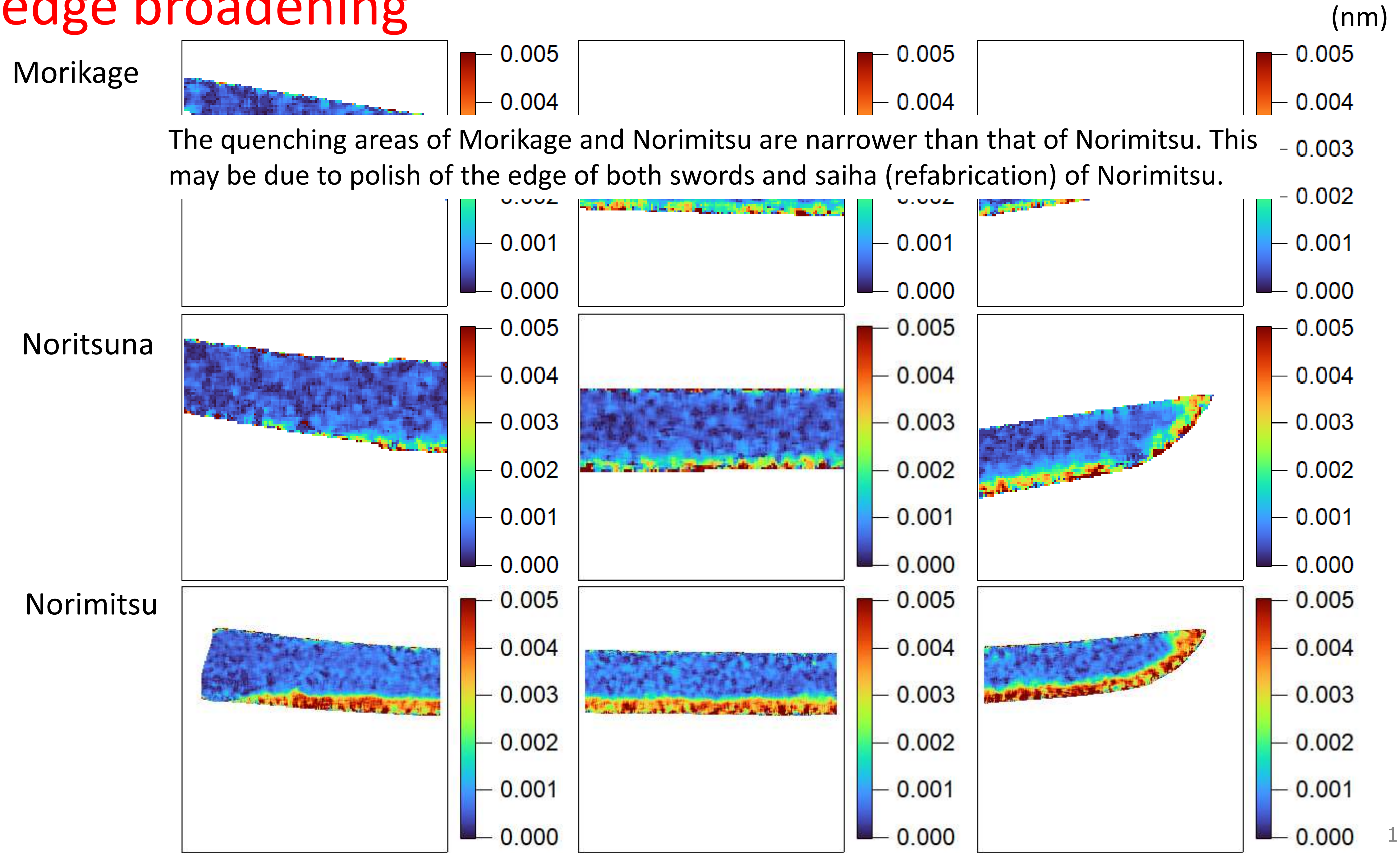
Noritsuna

Norimitsu



There are no larger lattice placing at backsides.
Almost no strain exists there.

Bragg edge broadening

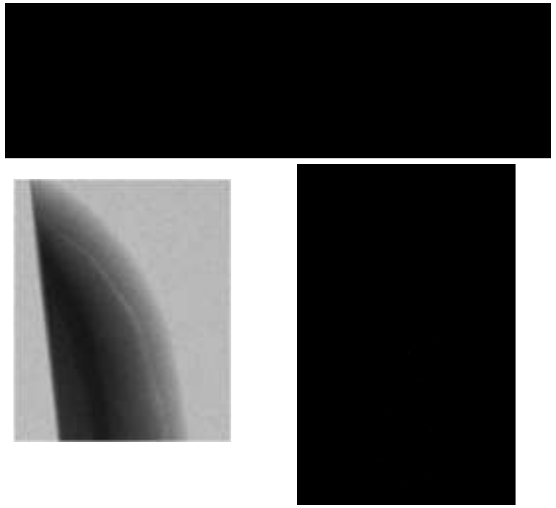


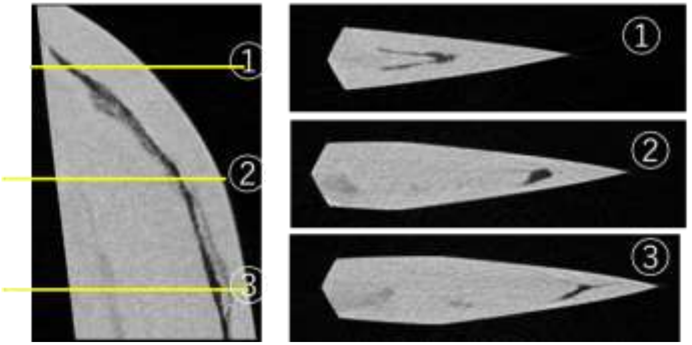
The quenching areas of Morikage and Norimitsu are narrower than that of Norimitsu. This may be due to polish of the edge of both swords and saiha (refabrication) of Norimitsu.

CT images of Morikage and Norimitsu

Norimitsu

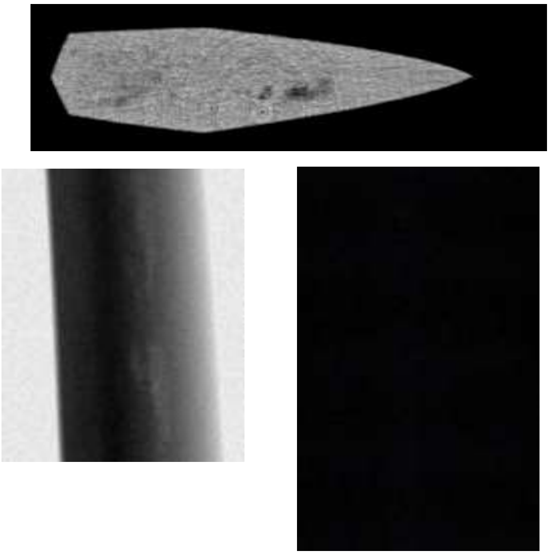
■ Near point (0.1㎜ thickness)

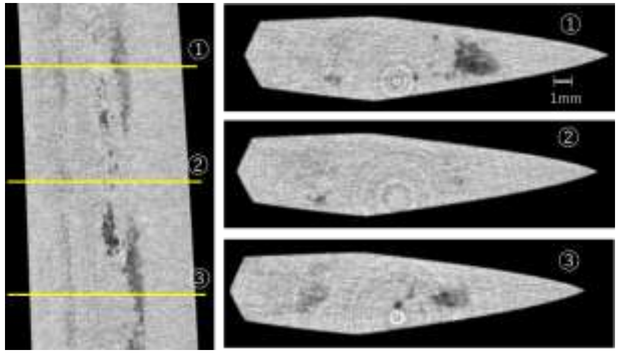




There is a void, which is considered to be due to gap produced by lapping core iron with surface iron.

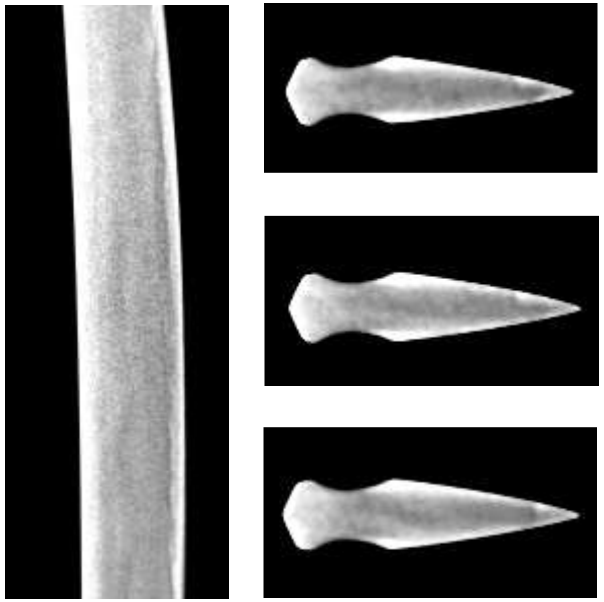
■ Central part (0.1㎜ thickness)





K. Oikawa et al., submitted to Scientific Report

Morikage



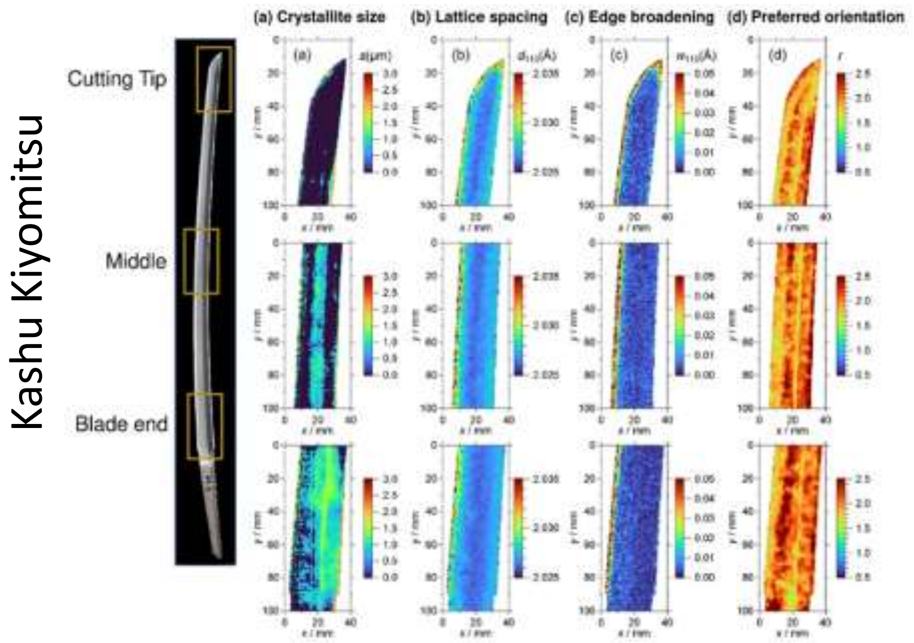
No clear structure in Morikage compared with Norimitsu.

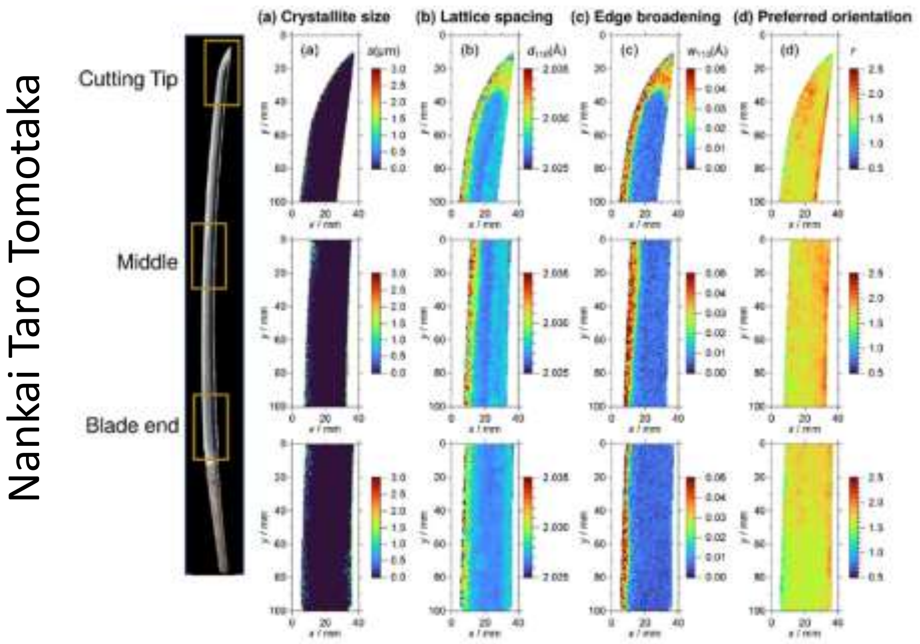
Norimitsu is a special case indicating a layered structure. From the similarity in the crystallite size distributions, the Bizen swords so far measured considered to have a layered structure: low carbon content at backside and high carbon content at edge side.

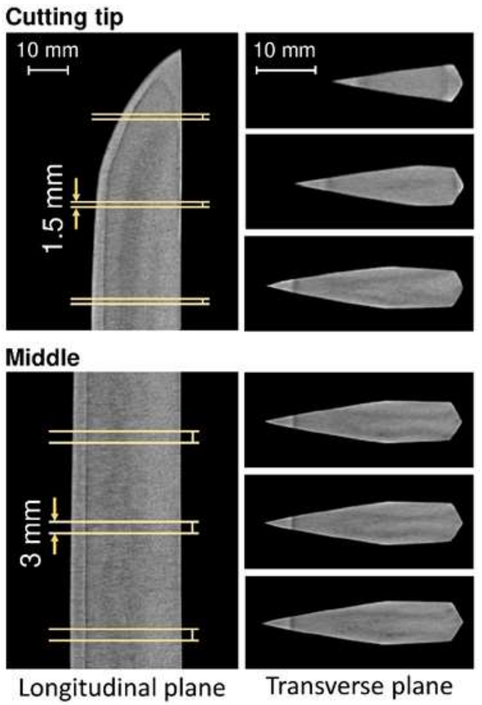
Swords with different type crystallite size distributions

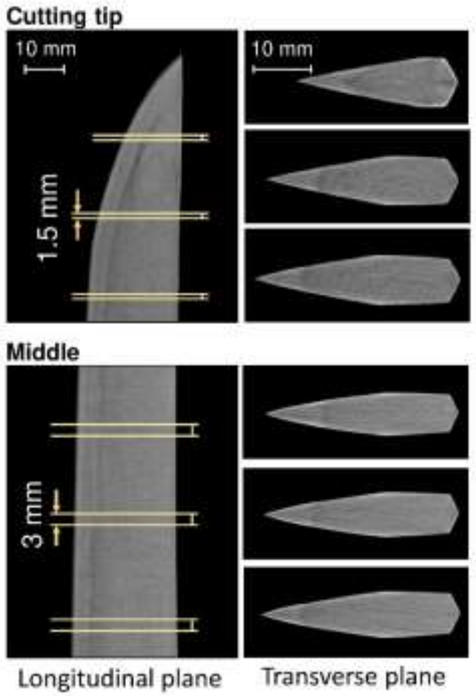
(Reference)

Y Matsumoto, K Oikawa, K Watanabe, H Sato, J D Parker, T Shinohara , Y Kiyanagi: Nondestructive analysis of internal crystallographic structures of Japanese swords using neutron imaging, Journal of Archaeological Science: Reports 58 (2024) 104729.









CT of Kashu Kiyomitsu indicates a layer structure as in the crystallite size distribution but that of Nankai Taro is homogeneous. A straight narrow quenching area is observed in Kashu Kiyomitsu and wider one in Nankai Taro.

Crystallite size distribution is different each other as shown before.

Lattice spacing distribution is similar each other. Larger lattice spacing appears at backsides of both swords.

Quenching area is broader in Nankai Taro. This will be due to straight wave-pattern in Kashu Kiyomitsu.

Texture is stronger for Kashu Kiyomitsu than Nankai Taro. This may be due to layered structure of Kashu Kiyomitsu, which would need forge welding. Nankai Taro may be made with a monolith iron with higher carbon content.

Summary

Metallurgical characteristics of Japanese swords have been studies by using neutron Bragg edge transmission and CT. Muon was also used to measure the carbon content.
(Neutron diffraction is also powerful tool, although it was not used here.)

- Crystallite size distributions were categorized into several patterns.
- Bizen swords we measured are considered to have a layered structure composed of steels with low and high carbon contents.
- The swords showing different crystallite size distributions indicated different features in CT and different or similar trend in Bragg edge transmission.

Further consideration is required to understand some of the observed characteristics in the measured results.

These measurements were performed under the proposal of J-PARC proposals of 2017A0099, 2020B330, 2021B0248, 2022A0154, 2022B167, 2022B315, 2023A0177 and 2023B239.