Volume-Based Shape Analysis for Internal Microstructure of Steels

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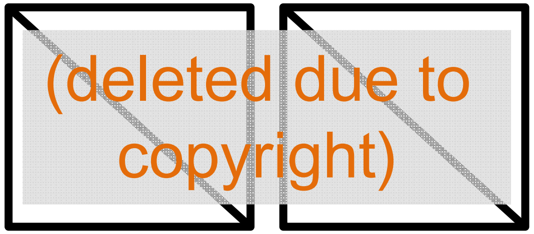
2014/10/30 (Thu)
IEEE International Conference on Image Processing (ICIP2014)

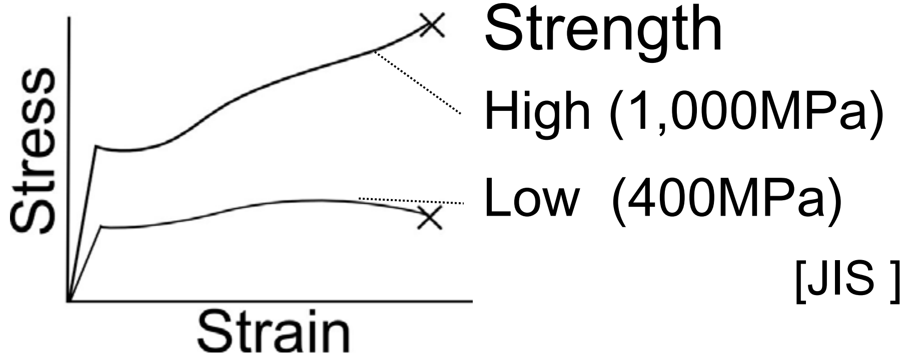
Importance of microstructure

Micro structures



- Same composition
- Different structure/ history (3D/4D)

Properties



Different properties
(Strength, heat resistance, etc)

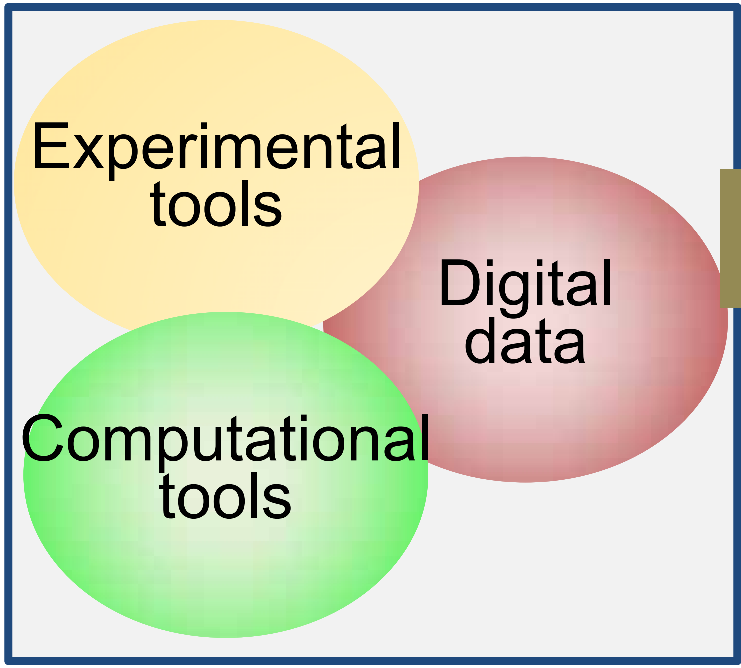
Micro-structures significantly affect properties.

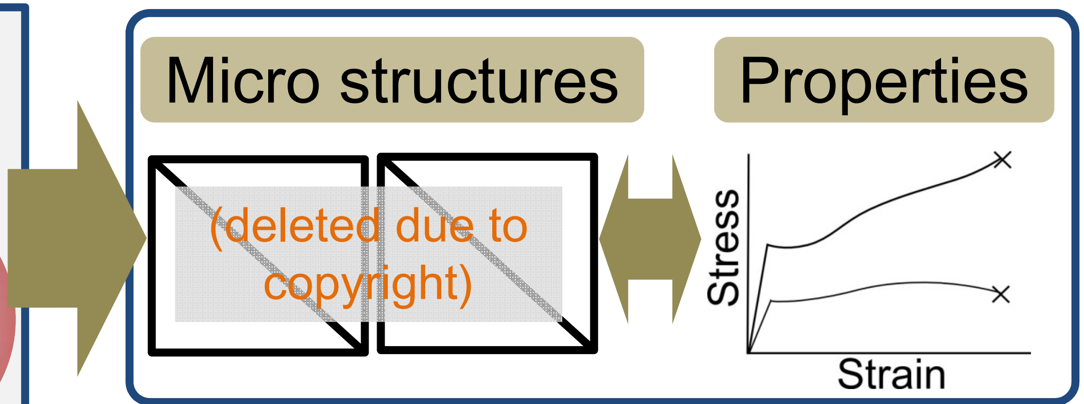
New global trend

Computer-aided material designing:

Simulate and design microstructures and properties

Materials genome initiative in USA [OSTP 2011]





Accelerate advanced materials discovery and deployment at least twice as fast as possible.

Japan has also started project "Materials integration". [2014]

What's our chance?

Image-based materials genome

Micro structures

Image processing

Geometric characterization

Properties

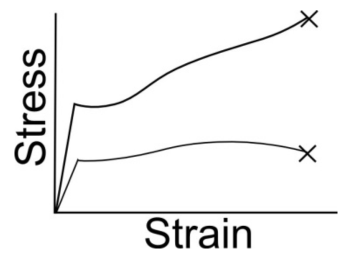


Image processing will be a key for materials genome.

We propose a new framework for 3D micro-structure evaluation based on image processing.

Focus on bearing steel

Bearing : Mechanical element to support rotating shaft.

(deleted due to copyright)

Automobiles

Trains

Industrial robots

High strength requirement than normal steel.

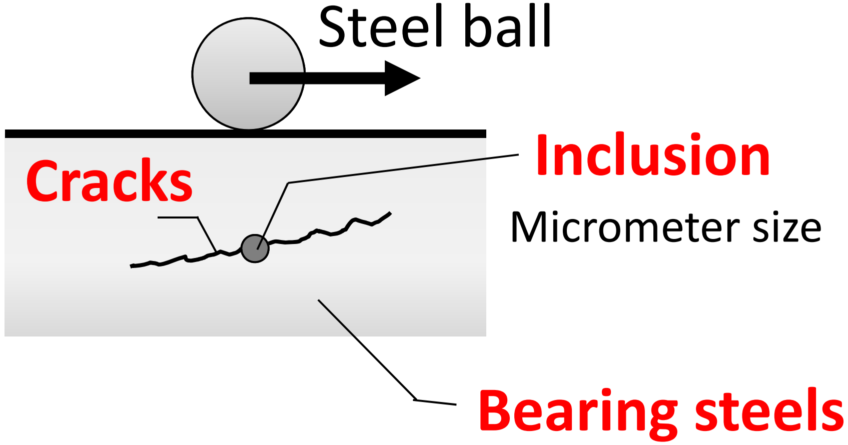
Huge real-world applications.

Fatigue failures of bearing

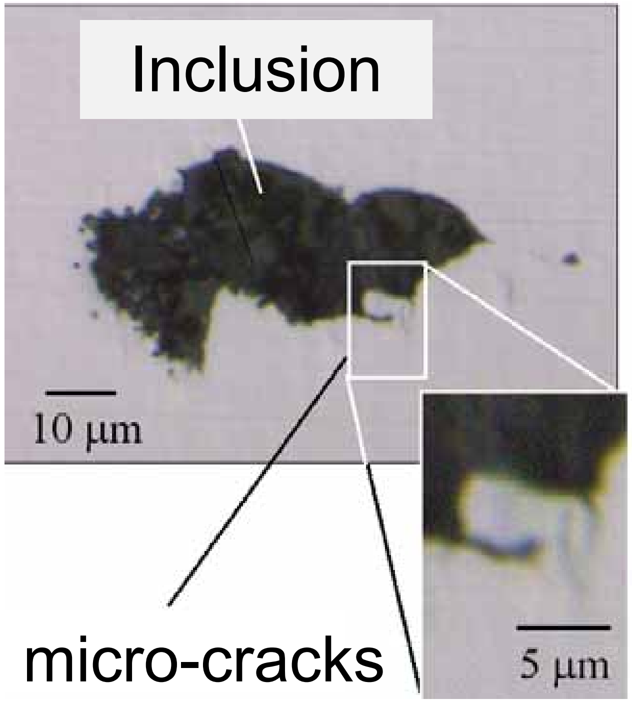
High stress condition

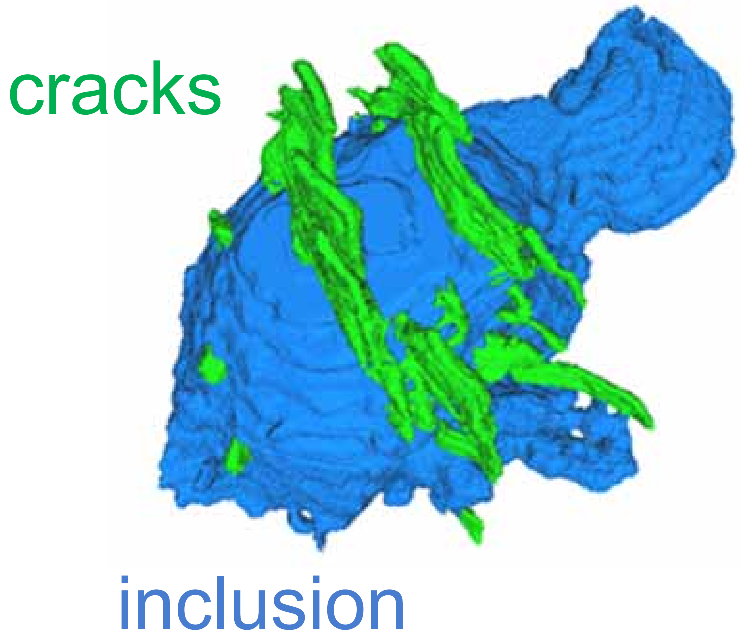
Contamination

→ Crack initiation & propagation



What shape features of inclusion will affect?





Complex shapes: Anisotropy and surface roughness of inclusions will cause crack initiation. [Cyril2008]

Our goal : 3D imaging and shape analysis technique.

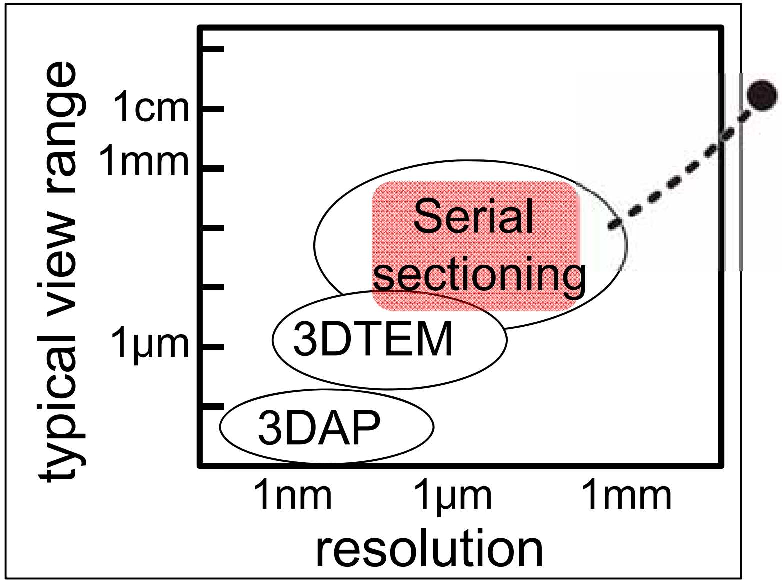
Related imaging technique of steels

Require 100 nano resolution & millimeter region !

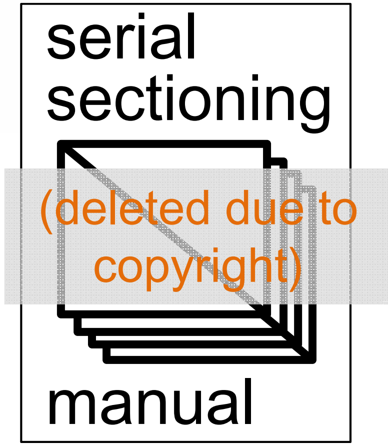
2D (general)

polishing,
microscope

3D (recent)



suitable for bearing steel

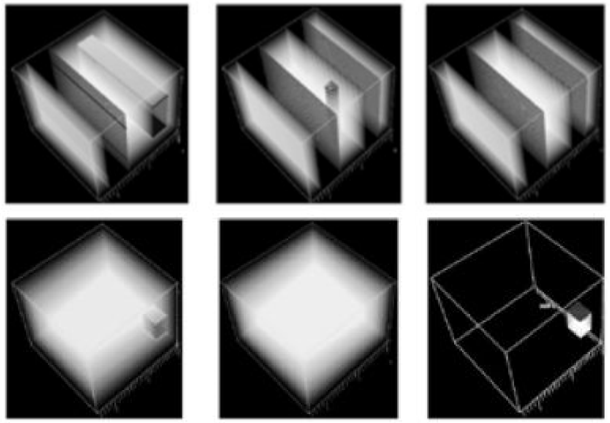


Difficulty

3D imagings have been developed.
But, not enough in resolution, view range, or labor cost.
For example, X-ray CT is unavailable to steels unfortunately.

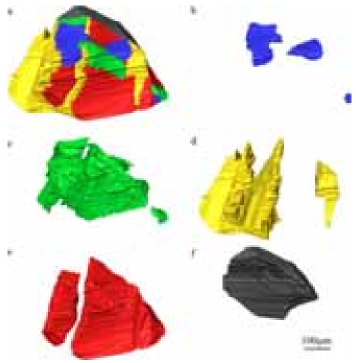
Related 3D shape analyses of steels

Topology [Adachi 2010]

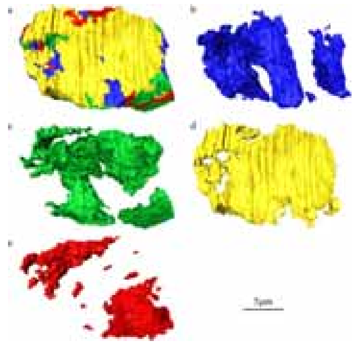


genus, Euler number

3D morphology [Morito2013]



ultra low carbon



high carbon

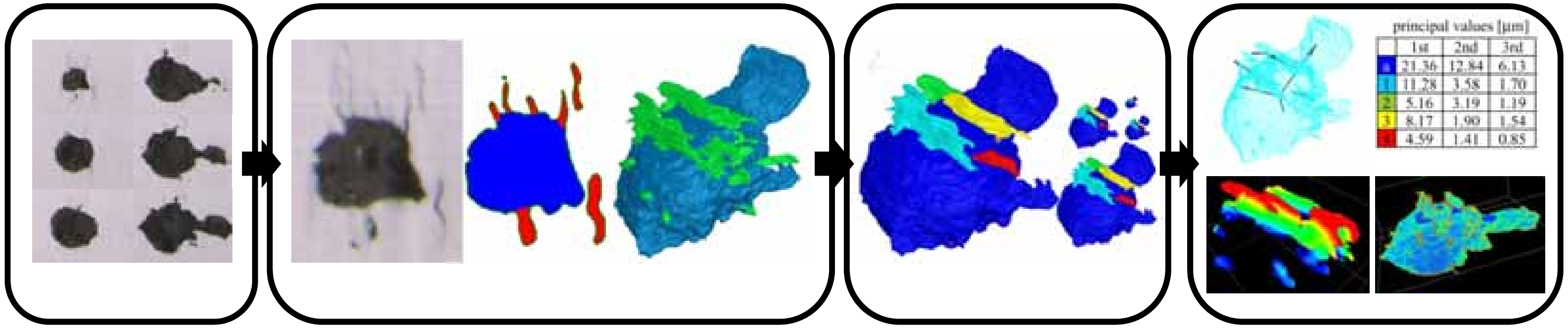
volume ratio of micro-structures

Difficulty

3D shape characterization of steels are at early stage.
Only a few frameworks exist for dealing with steel volumes.

Our approach

Framework



Imaging device | Segmentation | 3D shape analysis

3D, Precise
Automatic

Automatic labeling

Multi-resolution analysis

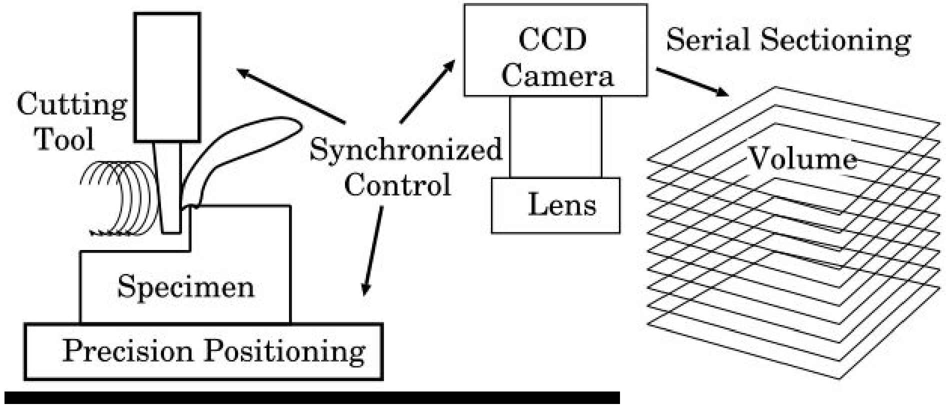
Shape:
Anisotropy, Roughness,
+ Other features

Our imaging technique

3D internal structure microscope

Automatic serial-sectioning device

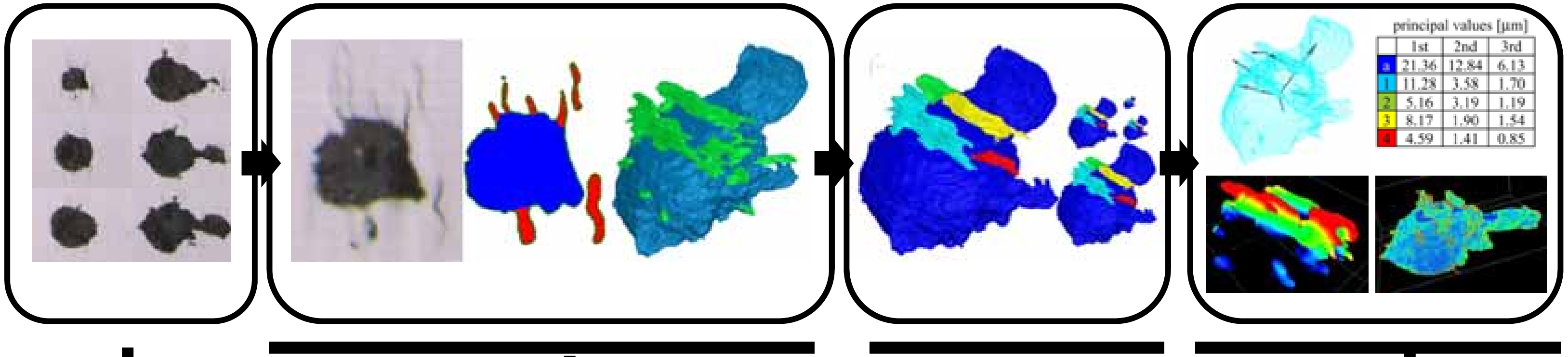
Automatic serial-sectioning



Precision cutting + Optical imaging → Volumetric Image

Feature:

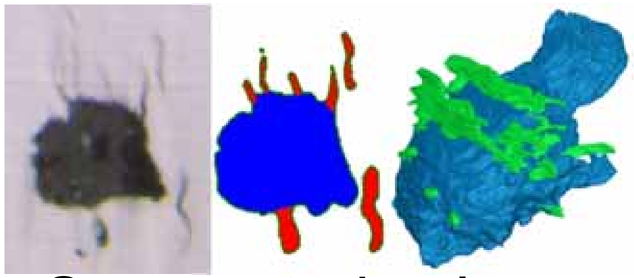
Automatic: Labor-saving
Precise: High resolution
Sufficient image alignment
Efficient : Months → Hours or days



Imaging device Segmentation Labeling

3D shape analyses

Segmentation



Segmented volume

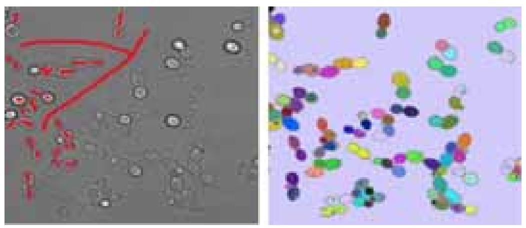
Limited in simple method.

Threshold of intensity
&
Manual segmentation

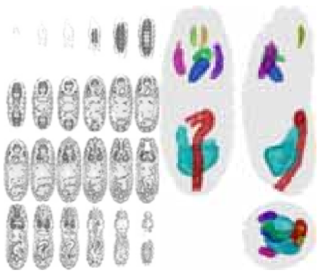
Future work to incorporate, …

Supervised Segmentation

- Pattern recognition
- Machine learning



[Straehle 2013]



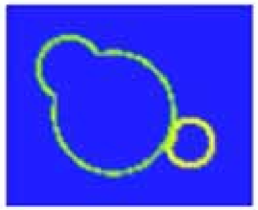
[Barron2013]

Unsupervised Segmentation

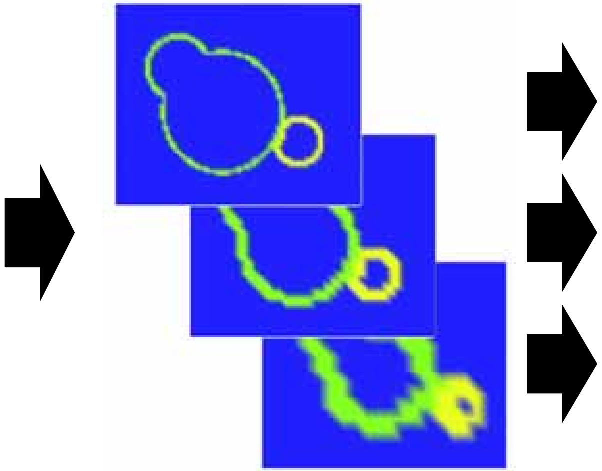
- Otsu's method [Otsu 1979]
- Snake (Active Contour)
- Graph Cuts
- Mean Shift
- Water Shed (Region Growing)

Multi-resolution analysis

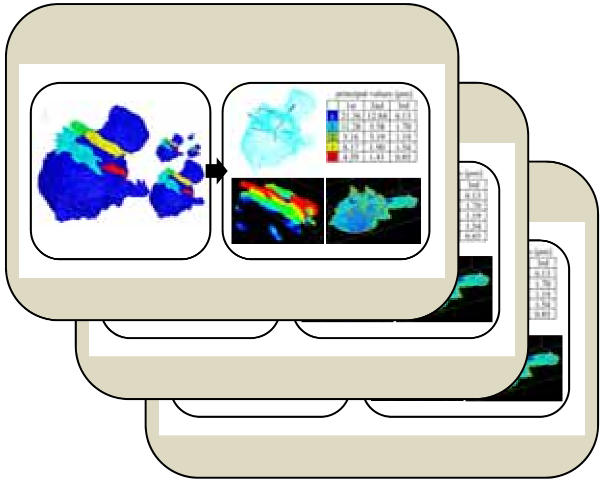
Labeling and analysis in each resolution.



(Input)
Segmented image



Multi-resolution pyramid



Labeling & shape analysis

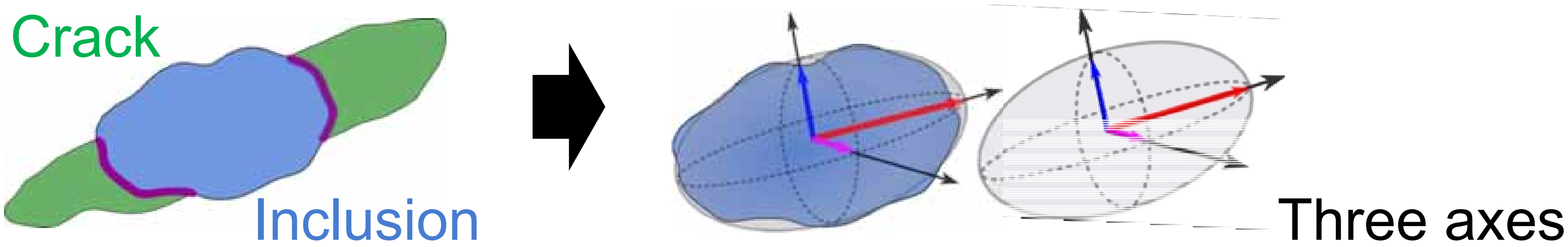
Multi -resolution & -material methods

Laplacian pyramid [Burt 1983]
+ Sethian's method [Sethian 1996]

Detail to Global feature

Anisotropy analysis

Principal component analysis (PCA)



PCA results corresponds to axes of ellipsoid fitting.

Eigen values: $\lambda_1, \lambda_2, \lambda_3$ ⟷ Axes length
Eigen vectors: $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$ ⟷ Axes direction

Application

Ratios of Eigen values ($\lambda_1/\lambda_2, \lambda_1/\lambda_3, \lambda_1/\lambda_3$) give anisotropy of inclusions. ⟷ Crack initiation

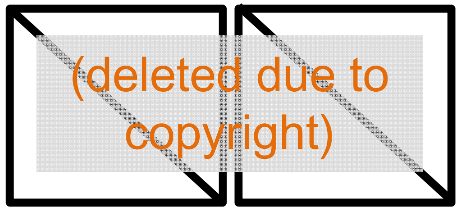
Roughness analysis

Surface curvatures

- Principal curvatures κ_1 and κ_2
- Gaussian curvature $\kappa_1 \kappa_2$
- Mean curvature $(\kappa_1 + \kappa_2)/2$
- Total curvature $\kappa_1^2 + \kappa_2^2$

+ Their statistical values
  (Max, Min. Mean, Histograms, etc)

e.g. Gaussian curvature and 3D shapes



$\kappa_1 \kappa_2 < 0$ $\kappa_1 \kappa_2 = 0$ $\kappa_1 \kappa_2 > 0$

Application

Inclusions

Surface roughness

Cracks

Initiating points
Existence of cracks

Discrete algorithm

Least-squares polynomial fitting Method
[Yoshizawa 2008]

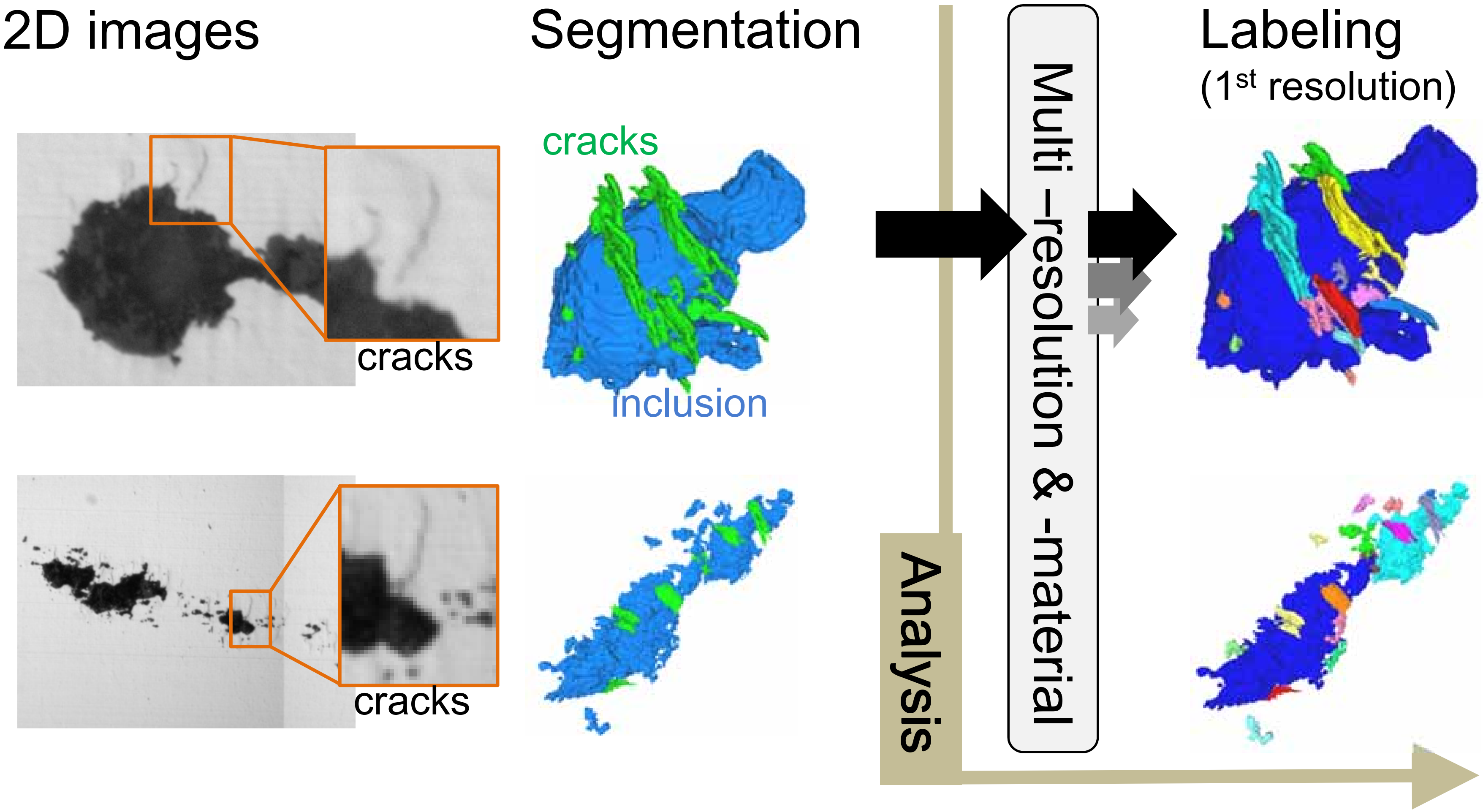
Experiment

- 3D Imaging & segmentation
- Labeling
- Anisotropy analysis (PCA)
- Roughness analysis (Curvature)

of

real-world bearing steels provided by a steel company.

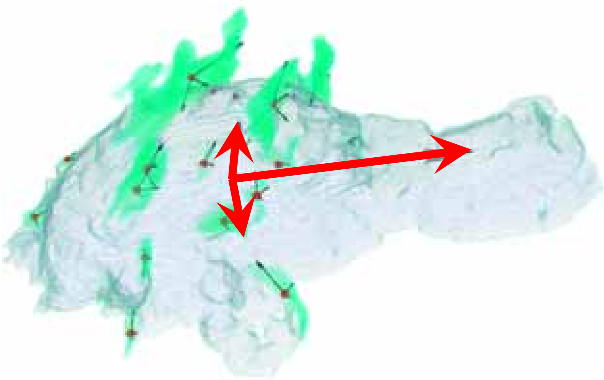
Experiment - Imaging, Segmentation & Labeling-



Detailed images of Inclusions and micro-cracks.
Automatically labeled images.

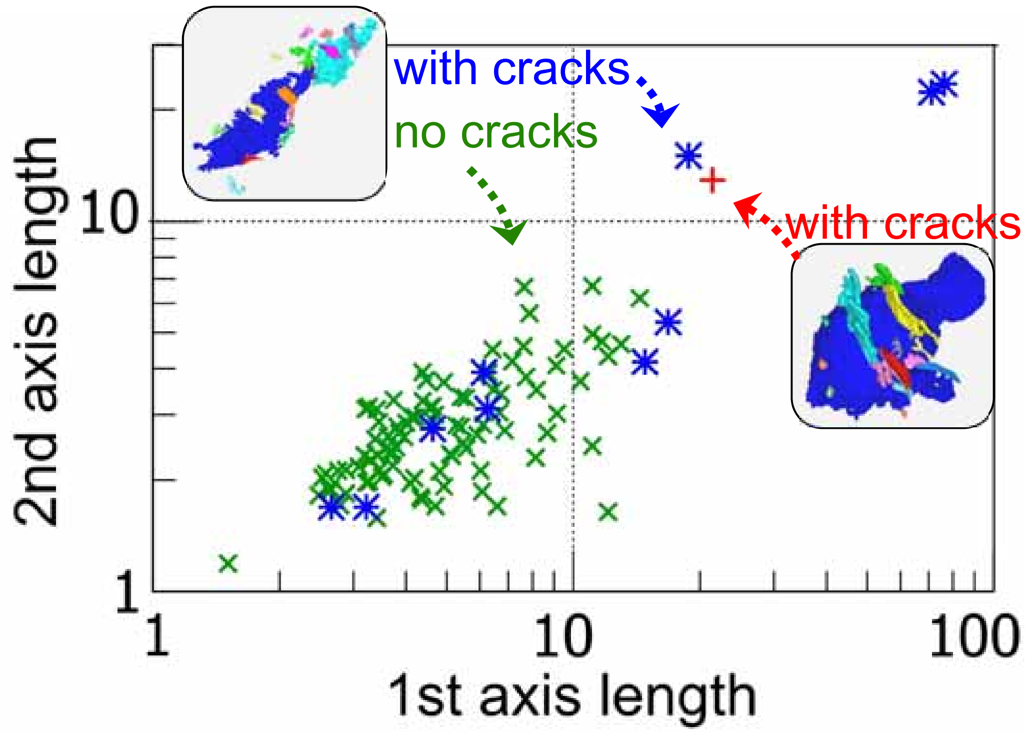
Experiment -Anisotropy (PCA results) -

Axis length ratio of inclusions



PCA axes

Plotting ratio



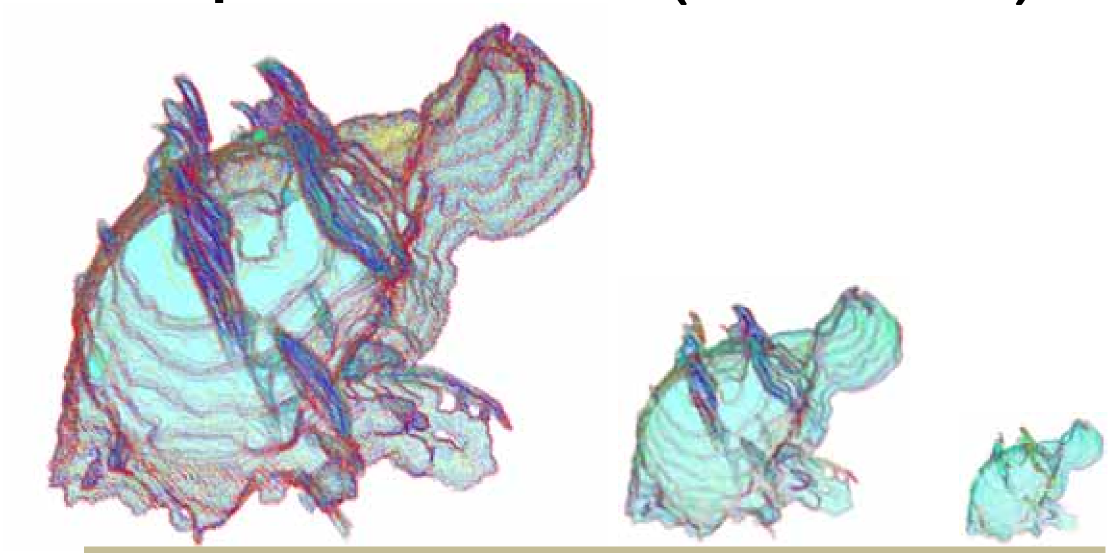
Anisotropy was characterized from three axes.

Discussion

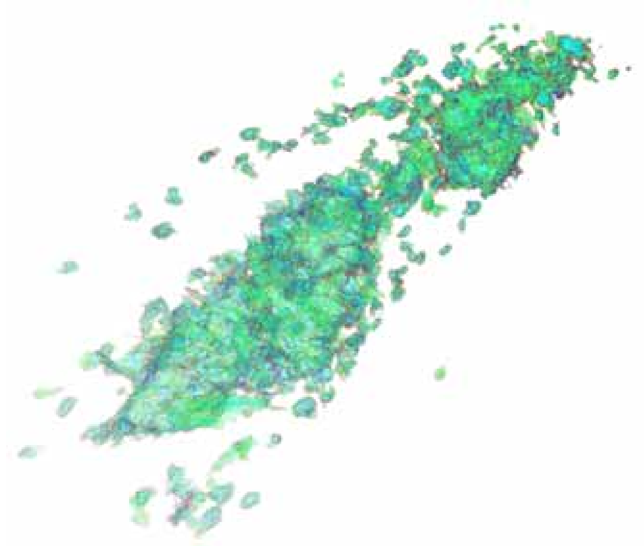
Previous literatures use anisotropy,
but difficult to characterize crack-initiating inclusions.

Experiment -Roughness-

Principal curvature (maximum)



Multi-resolution

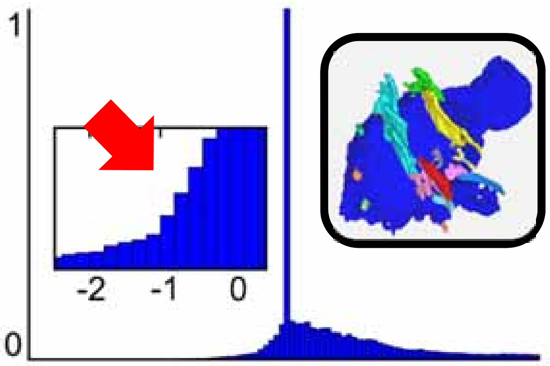


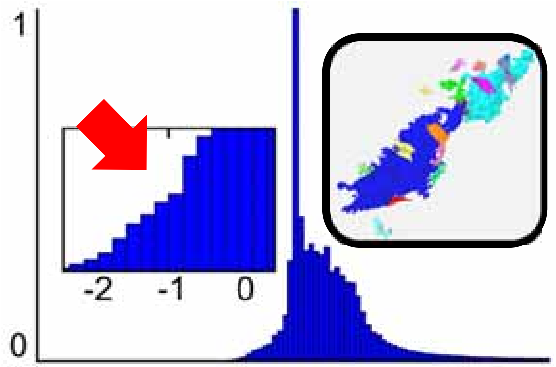
Roughness was calculated from 3D images.

Statistics

Maximum, minimum, mean, median, histograms are also calculated.

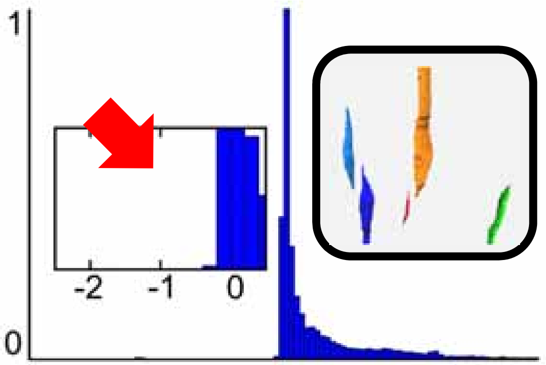
Experiment -Histogram of max principal curvature-

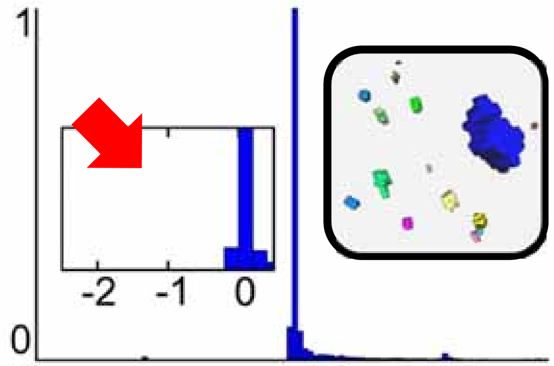




Specimen
with cracks

slope in negative
region → concave





Specimen
without cracks

Almost no slope in
negative region

New hypothesis based on quantitative analysis

Additional histogram analysis of curvature implied concave regions were important for initiating cracks.

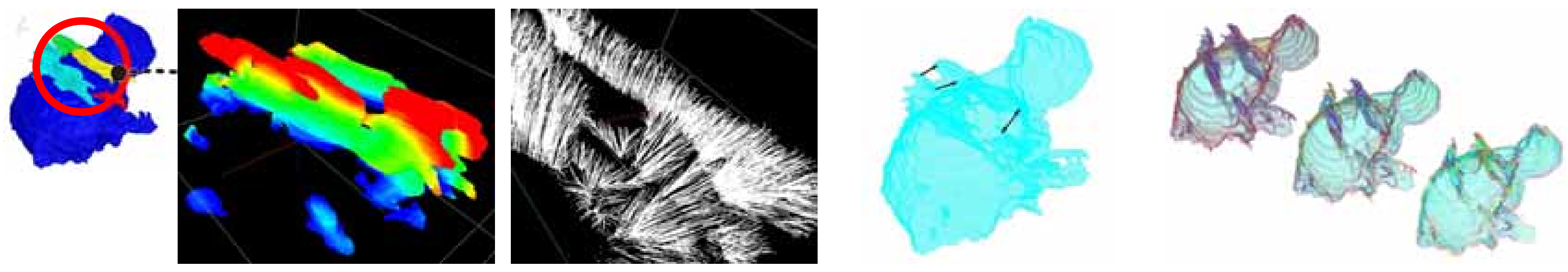
Limitations & Future work

Limitations

- **Simple** segmentation
- Limited **shape parameters**

Future work

- Incorporating sophisticated segmentation
- Using **other shape parameters & features**



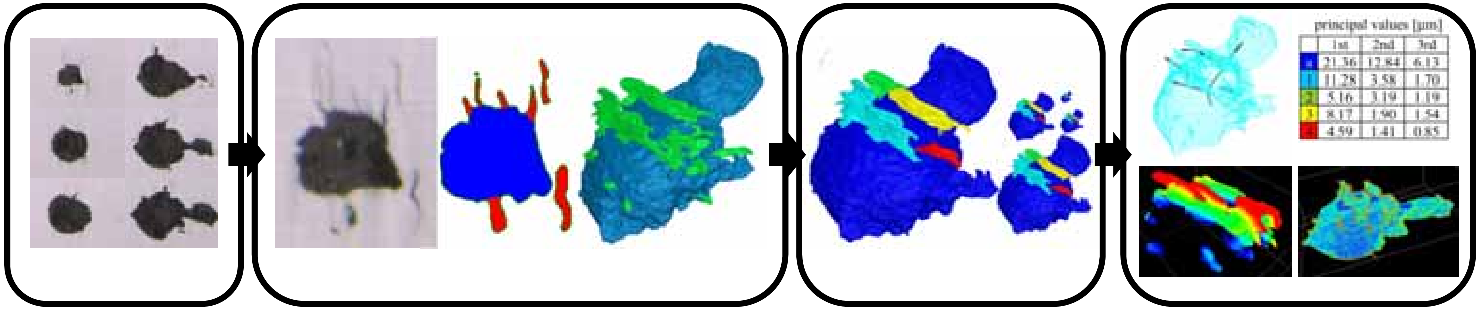
Distance field Streamline Min. distance Multi-resolution

etc.

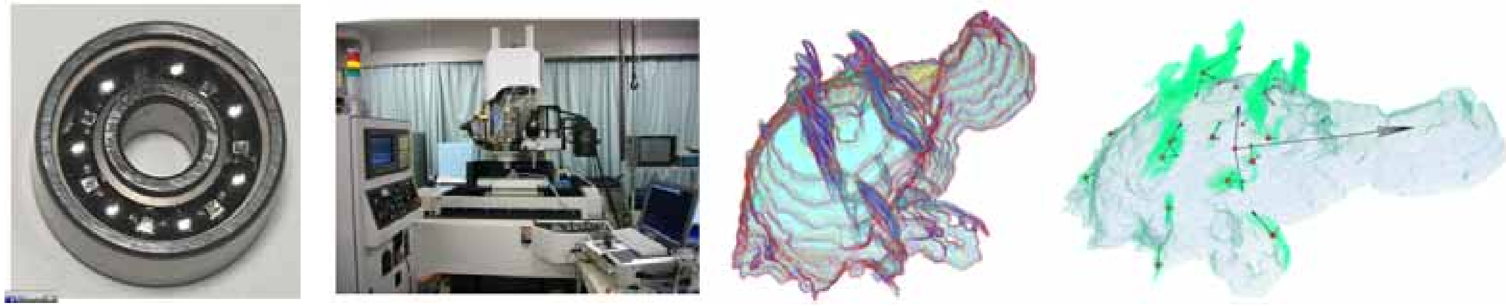
- More specimens, other materials

Conclusion

- We proposed image-based materials genome.
- We constructed a novel framework with efficient 3D imaging and shape characterization of steels.



Imaging Segmentation Labeling Shape analysis



Curvature analysis implied concave regions was important for initiating cracks.