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EPMA™-8050G Electron Probe Microanalyzer

Application News

Evaluation of EV Drive Motor Shaft Produced by Radial Forging: Elemental Mapping Analysis by EPMA

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User Benefits

- EPMA elemental analysis makes it possible to evaluate processing technologies and the material strength of hollow shafts produced by radial forging.
- The elemental distribution that causes fiber flow (metal flow) can be understood.
- It is possible to identify material internal defects and evaluate strength improvement by evaluation of the elemental distribution of inclusions and precipitates.

■ Introduction

In recent years, the trend toward decarbonization for reduction of greenhouse effect gases (GHG) has accelerated. As part of those efforts, the shift to electric vehicles (EVs) in the automotive industry is playing a large role in realizing decarbonization. Because improvement of the vehicle cruising range is required for popularization of EVs, reduction of vehicle body weight has been taken up as a development theme. In particular, weight reduction of EV drive motor shafts has become an important development theme not simply as a means of extending the cruising range, but also because improved motor response can be expected due to the reduced inertial force. Radial forging is a new forging technology for hollow shafts which makes it possible to form the inner and outer diameters simultaneously by applying force from the radial direction of hollow shafts or hollow axis with a hammer (die) while inserting a core bar into the shaft to transcribe the inner diameter shape [1]. Since hollow shafts produced by the radial forging process satisfy both strength and weight reduction requirements, these products have attracted attention as next-generation shafts.

As part of a multi-faceted evaluation of motor shafts produced by radial forging introduced previously in other Application News articles [2), 3), 4)], this article introduces an example of application of an elemental mapping analysis by the EPMA-8050G electron probe microanalyzer, focusing on inclusions and fine precipitates.

■ Observation of Test Pieces and Wide-Area Mapping Analysis

The test material used in this experiment was SCr420. Test pieces were cut out from the unprocessed material (Blank) and two types of radial forged products (reduction of area: 50 %, 70 %), and were prepared by surface polishing. Here, "reduction of area" (RoA) refers to the percentage change in the cross-sectional area before and after forging. The colored areas in Fig. 1 show the sampling positions of the Blank and the two radial forged products (RoA: 50 %, 70 %). Fig. 2 and Fig. 3 show images obtained by observation of the fiber flow (metal flow) after chemical treatment of the cross sections of the 50 % RoA processed equivalent product. The distribution of Cr in the elemental mapping image shown in Fig. 4 is overlaid on the area indicated by the arrow in Fig. 3. The flows of the fiber flow lines in Fig. 2 and Fig. 3 show good agreement with the elemental distribution of Si, Cr, and Mn. In Fig. 4, it can be understood that the surface area has a fine structure, while in the deep region, the flows of the structure are thick and the differences in intensity are large. Thus, although it is not clear from the results of observation with an optical microscope that refinement of the fiber flow is caused by forging, this can be clearly observed thanks to the high resolution of EPMA.

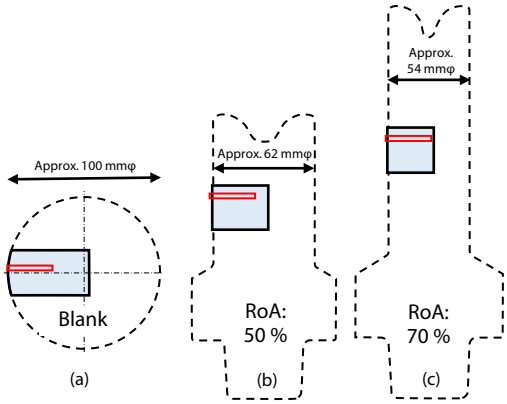

Fig. 1 Test Piece Sampling Positions and Measurement Positions
(a) Blank, (b) Radial Forging Product (RoA: 50 %),
(c) Radial Forging Product (RoA: 70 %)
(Samples courtesy of Tsuzuki Manufacturing Co., Ltd.)

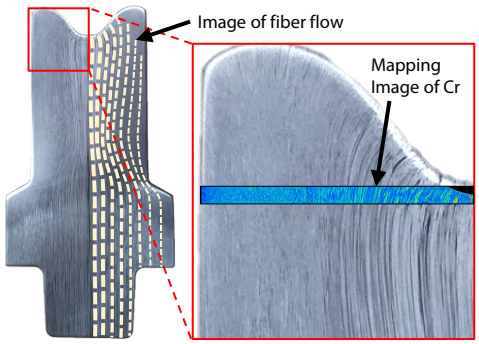

Fig. 2 Image of Observation of Fiber Flow of Cross Section (RoA: 50 %)

Fig. 3 Enlargement of Fiber Flow Observation Image and Mapping Image of Cr

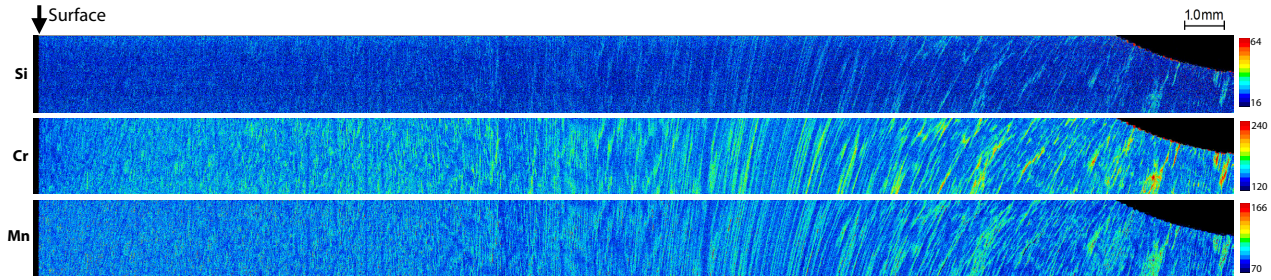

Fig. 4 Elemental Mapping Image of Radial Forging Product (RoA: 50 %) (Equivalent to Area in Black Box in Fig. 3)

■ Comparison of Blank and Radial Forging: Surface and Internal Microstructure and Inclusions

Fig. 5 and Fig. 7 show the results of a wide-area elemental mapping analysis of the areas in the red boxes of the Blank and the radial forging product (RoA: 70 %) in Fig. 1, and Fig. 6 and Fig. 8 show the results of a narrow-area elemental mapping analysis of the near-surface region and the interior region approximately 24 mm from the surface of the respective samples. Looking at Fig. 7 and Fig. 8, in the radial forging product, flow of the microstructure along the direction parallel to the surface can be seen in Si, Cr and Mn, and that flow has become unidirectional, without undulations like those in Fig. 4. It is conjectured that this is due to changes in the flow of the microstructure depending on the sampling position, as in the case of the fiber flow in Fig. 2 and Fig. 3. In the backscattered electron image (BEI), images reflecting the crystallographic orientation were captured by channeling contrast, and a tendency of the crystal grains to become finer as a result of forging can be observed. Comparing the distribution of C, it can be understood that the radial forging product has a finer microstructure than the Blank. It is also clear that S forms MnS inclusions, as S has the same distribution as the Mn enriched region. In the radial forging product, these have a slender, elongated shape, as they were crushed in the direction perpendicular to the direction of forging applied from the surface, and particularly in the interior, they exist as large masses.

Where these features are concerned, when the heated material undergoes natural cooling in the process of radial forging, it can be inferred that segregation of the internal microstructure proceeds by moderate microstructural change due to the heat effect, whereas refinement of the microstructure proceeds in the near-surface region because the effect of forging is greater in the near-surface region than in the interior.

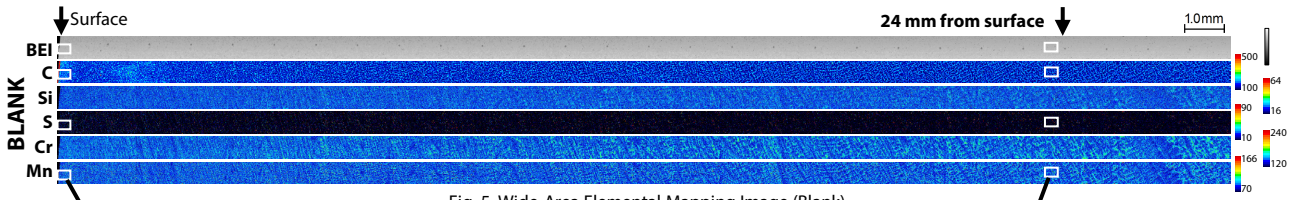

Fig. 5 Wide-Area Elemental Mapping Image (Blank)

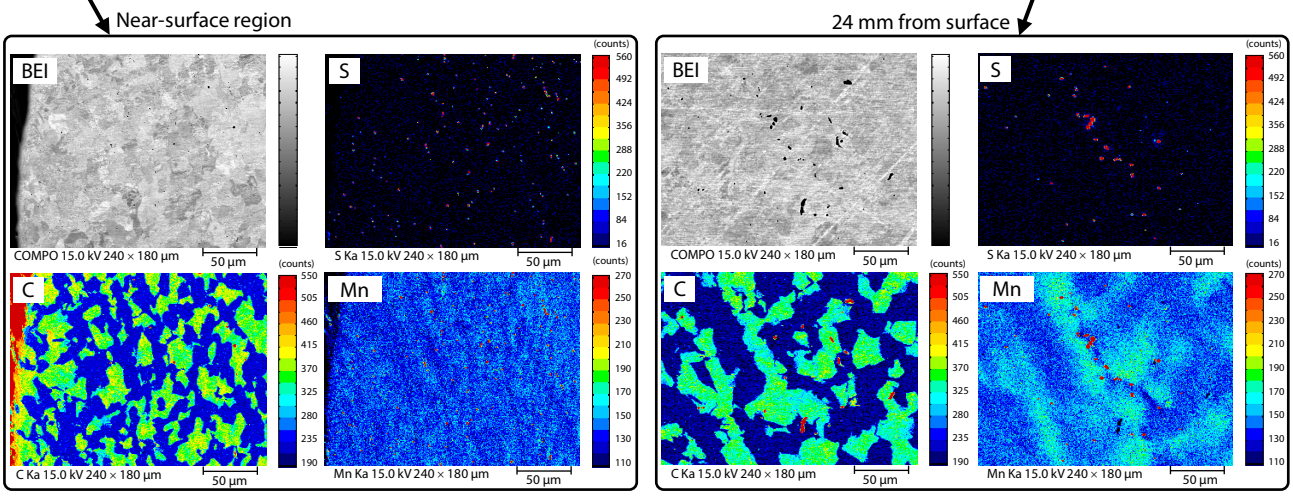

Fig. 6 Narrow-Area Elemental Mapping Images (Blank)

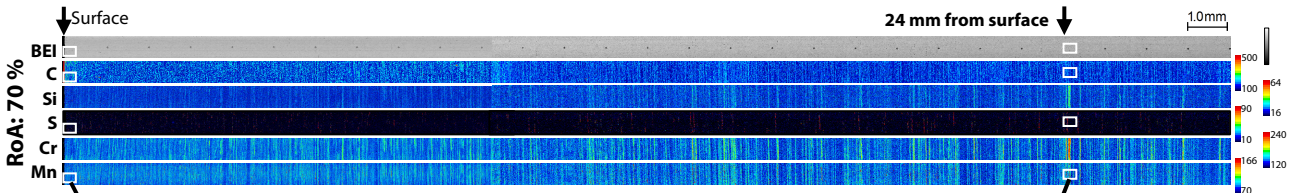

Fig. 7 Wide-Area Elemental Mapping Image (Radial Forging Product, RoA: 70 %)

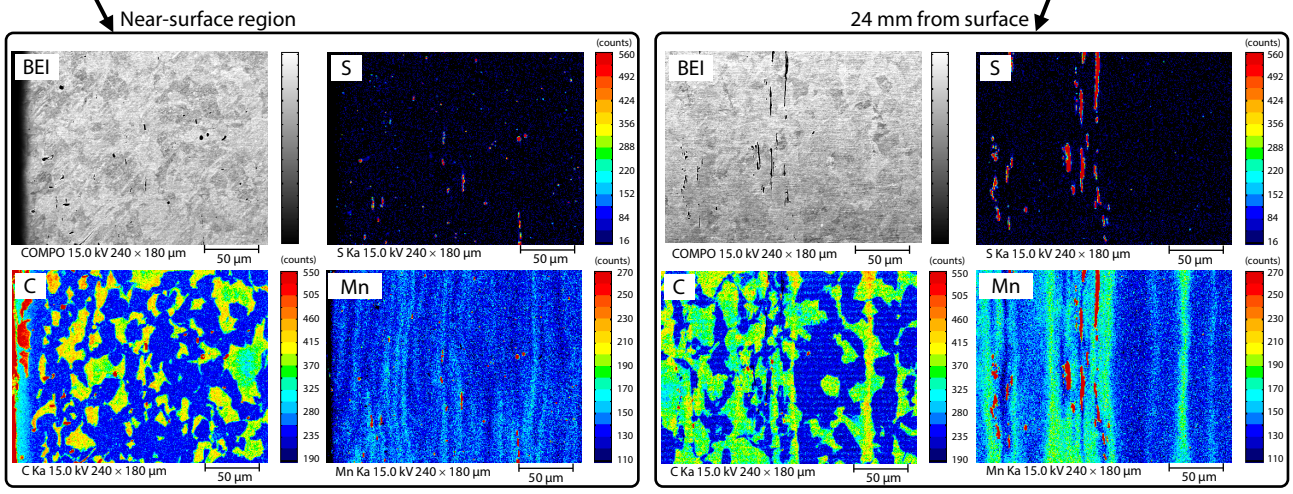

Fig. 8 Narrow-Area Elemental Mapping Image (Radial Forging Product, RoA: 70 %)

■ Comparison of Blank and Radial Forging: Pearlite Structure and Grain Boundaries

Fig. 9 shows the enlarged elemental mapping analysis results for the near-surface regions of (a) Blank and radial forging products with (b) RoA: 50 % and (c) RoA: 70 % in Fig. 1. Looking at the distribution of C, a lamellar fine pearlite microstructure can be seen. (Pearlite is a microstructure which is separated into the two phases of ferrite (α iron) and cementite (Fe_3C).) With further enlargement of the area in the 70 % RoA forging in Fig. 9, as shown in Fig. 10, it can be seen that the distribution that appeared to be island-like in Fig. 9 is also fine pearlite, and its interlamellar spacing is narrower than those of the Blank and the 50 % RoA forging.

It is known that strength generally increases as the interlamellar spacing of pearlite becomes narrower, and this is considered to be an effect of forging. Looking at the distribution of Cr, because grain boundaries have formed and at those grain boundaries, the distribution of N coincides with the Cr-enriched areas, it can be understood that Cr nitrides have formed. These Cr nitrides also tend to be finer in the radial forging products in comparison with the Blank, and this is also considered to be an effect of forging. It may also be noted that the distribution of Cr in Fig. 10 coincides with the distribution of C, indicating that carbides of Cr have also formed.

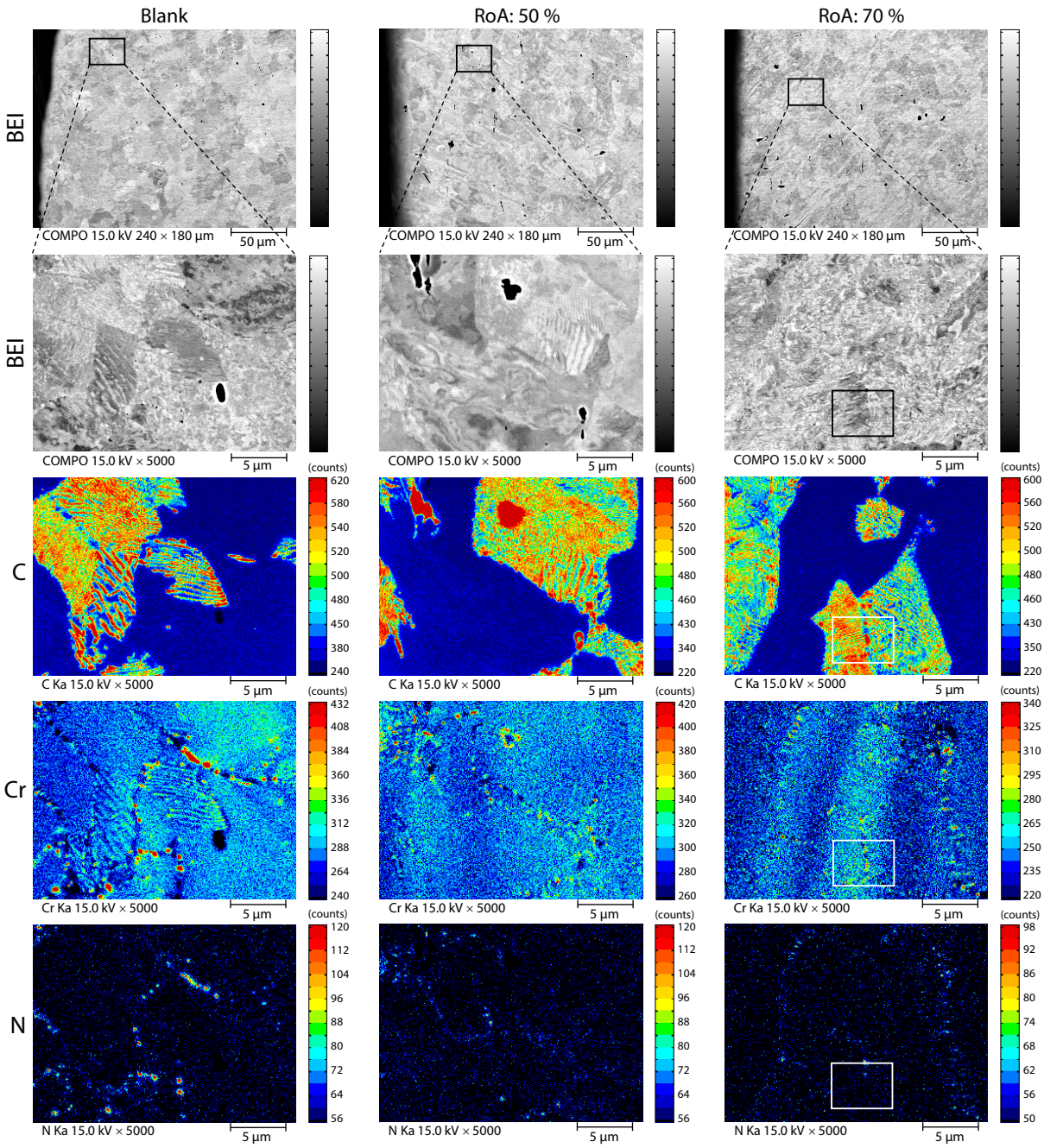

Fig. 9 Elemental Mapping Images of Near-Surface Regions of Each Test Piece

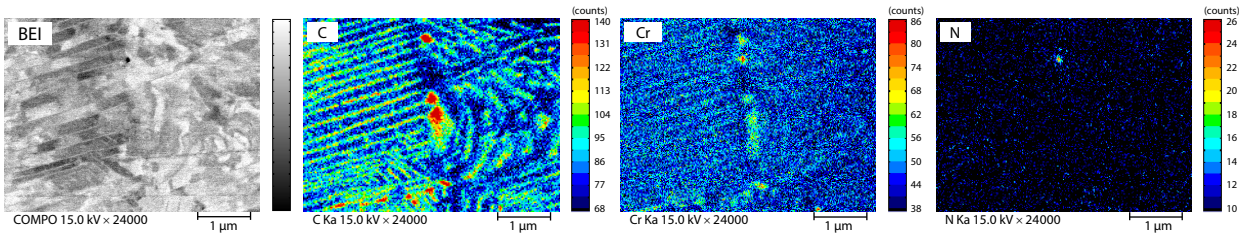

Fig. 10 Elemental Mapping Images of Near-Surface Region of Radial Forging (RoA: 70%) (Enlargements of Areas in Boxes in Fig. 9)

■ Elemental Mapping of Fine Precipitates and Compounds

A high-magnification elemental mapping analysis of the near-surface region of the radial forging product with the RoA of 70 % was conducted. Fig. 11 shows the elemental mapping analysis results in which the area of the near-surface region in Fig. 8 is under higher magnification, and Fig. 12 and Fig. 13 show the results of an elemental mapping analysis of these two areas when the magnification was increased further. Looking at the distribution of Cr in Fig. 11, there is a location (red box in Fig. 11) where Cr enrichment has occurred even in an area where C has not precipitated, and from the magnified view of this part in Fig. 12, it is thought that Cr precipitated as nitrides of Cr because its distribution is consistent with the distribution of N. Moreover, in Fig. 13, S, Mn, N, and Al were detected in minute regions, and when their distributions are shown by an overlaid image, it can be seen that MnS (manganese sulfide) and AlN (aluminum nitride) have formed adjacent to each other.

■ Conclusion

Elemental mapping analysis of metal materials using the electron probe microanalyzer (EPMA) makes it possible to identify elements that cause fiber flow, which cannot be determined by observation with an optical microscope. It is also possible to investigate the distribution and morphology of inclusions and investigate the formation of fine precipitates and compounds. Thus, the EPMA is a useful tool for understanding internal defects in materials and improving material strength in product manufacturing processes.

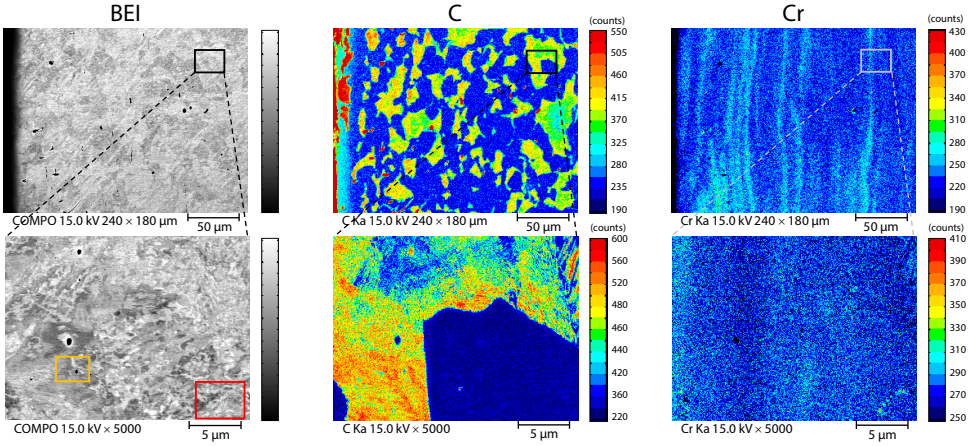

Fig. 11 Elemental Mapping Analysis Images of Near-Surface Region of Radial Forging (RoA: 70 %)

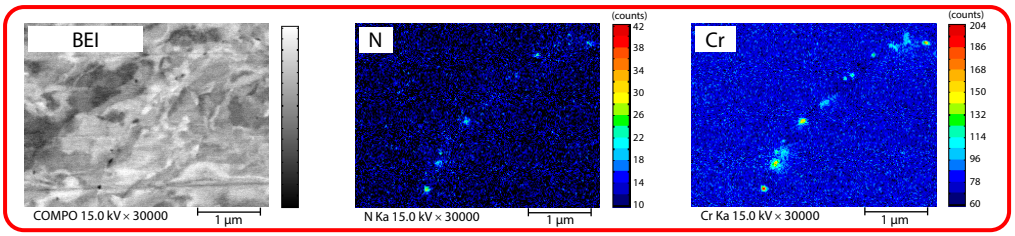

Fig. 12 High-Magnification Elemental Mapping Images of Near-Surface Region of Radial Forging (RoA: 70 %)
(High Magnification Images of Area in Red Box in Fig. 11)

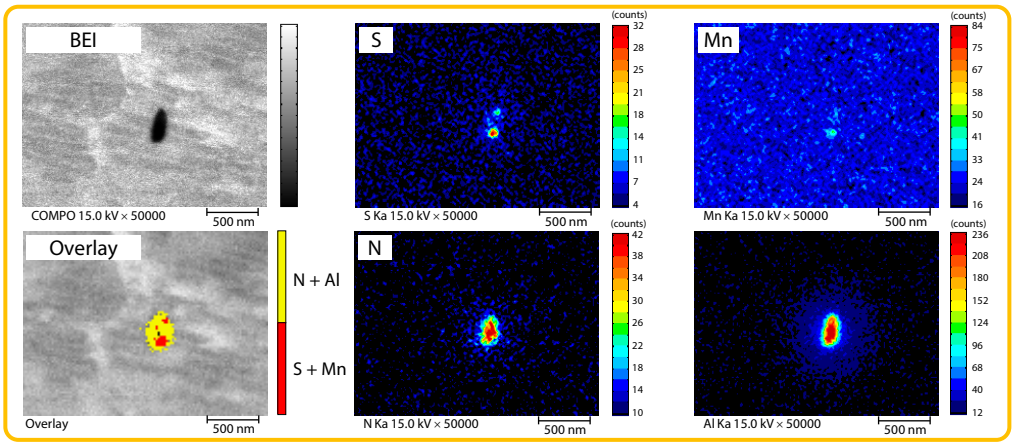

Fig. 13 High-Magnification Elemental Mapping Images of Near-Surface Region of Radial Forging (RoA: 70 %)
(High Magnification Images of Area in Orange Box in Fig. 11)

<References>
1) Tsuzuki Manufacturing Co., Ltd., Introduction of Shaft
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