Supplementary Materials for

**A macro-nano-atomic–scale high-throughput approach for material research**

Yiwei Ju, Shuai Li, Xiaofei Yuan, Lei Cui, Andy Godfrey, Yunjie Yan, Zhiying Cheng, Xiaoyan Zhong, Jing Zhu*

*Corresponding author. Email: jzhu@mail.tsinghua.edu.cn

Published 1 December 2021, *Sci. Adv.* 7, eabj8804 (2021)
DOI: 10.1126/sciadv.abj8804

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Other Supplementary Material for this manuscript includes the following:

Movie S1
**Supplementary Text**

**Introduction of the single-beam high-throughput SEM**

Conventional scanning electron microscopes (SEMs) are usually used to selectively analyze selected small areas (typically tens of μm) on a sample, due to the limited imaging throughput. In some research and applications, such as three-dimensional (3D) reconstruction of biological tissue, two-dimensional (2D) materials cross-scale characterization, and wafer inspection, it is necessary to image entire mm-scale samples with nm-scale resolution. Large area imaging also can avoid inaccuracies in standard structure characterization studies as a result of poor choices in image sampling. To achieve such data sets, increasing the throughput of a SEM is necessary. In a conventional SEM, the imaging rate for secondary electron (SE) detection is usually <20 Mpixels/s (3), and for backscattered electron (BSE) the detection rate is generally slower.

The high-throughput SEM system is designed to investigate mm-scale or cm-scale large areas or volumes with high resolution, allowing terabyte (TB)-level data analysis. A multi-beam SEM (mSEM) for use as a high-throughput SEM (3, 4) has been developed by Zeiss, where throughput is improved by increasing the number of primary beams. Multiple primary electron beams are generated in a single column and used for separate scan sub-field arrays. SEs from each scanning field are collected in each column and projected simultaneously to a detecting array. In this type of mSEM, BSEs images cannot be handled, as compared to SEs, BSEs have larger energy and wider energy range. Moreover, it is very hard to separate the returning BSE beams in a way that avoids cross talk in a multi-beam detection system. As such in a mSEM, the SE imaging throughput of each beam is not improved and remains the same as that in a conventional SEM.

To optimize data throughput in a single-beam SEM, a commercially available high-throughput single-beam SEM, Navigator-100 (Fig. S16), has been developed by Focus e-Beam Technology (FBT, Beijing, China). This microscope allows simultaneous imaging at high rates, not only of SEs but also of BSEs, with detection rates of up to 2 x 100 Mpixels/s (minimum dwell time = 10 ns/pixel). Improved imaging throughput is achieved by means of optimization of the electron optical system considering four different aspects: a) A special electron optical system that combines a high primary electron beam current and high resolution even at low landing voltages (1.8 nm@1 keV, 4 nA). Maintaining a high beam current for a given pixel dwell time results in a
good signal-to-noise (SNR) ratio in imaging; b) A detection system combined with the electron optical system that provides a high amplification factor and high electron signal collection efficiency; c) Direct electron detectors (DED) to minimize detection bandwidth, and d) A specially designed deflection system allowing an enlarged field of view (FOV), thereby increasing data acquisition in each single scanning frame.

Compared to the mSEM, this high-throughput single-beam SEM focuses on optimizing the image rate of single-beam to increase throughput instead of increasing the number of beams. It is more flexible in signal electron collection and more stable under different imaging conditions. Combined with real-time algorithms, the high-throughput single-beam SEM can be used for intelligent automatic high-throughput image analysis. In this work on cross-scale analysis of a single-crystal superalloy, high-throughput BSE imaging enables identification of different carbides, allowing related statistical data to be determined over a cm-scale area while maintaining nm-scale resolution.

**Principle of the single-beam high-throughput SEM**

**Electron optical system**

For a single-beam SEM, increasing the imaging speed requires shortening the pixel dwell time. However, at the minimum pixel signal collection dwell time, the SNR must still be high enough to allow features to be distinguished from background noise (47). From the point of view of electron signal generation, increasing the primary beam current helps to reduce the pixel dwell time at a minimum effective SNR condition. However, larger beam currents also result in a stronger Coulomb interaction effect of the primary beam, leading to reduced resolution. Additionally, from the point of view of electron signal collection, the detection system should be designed to collect as many signal electrons, including both SEs and BSEs, as possible, aiming to approach to the limitation of collection efficiency (100 %).

The SEM imaging rate, defined by number of pixels acquired per second, directly defines the imaging time of one frame (given by [dwell time × pixel number] + overhead for beam repositioning after each scan), is the main factor in determining image throughput. In addition to
the imaging rate, the SEM throughput is also influenced by several other factors, such as stage movement time, pause time, and focus adjustment time.

The electron-optical system of the Navigator-100 high-throughput SEM is shown in Fig. S17. The core of the microscope is a compound objective lens and detection system called the SORRIL™ (Swinging Objective Retarding Receiving Immersion Lens) column, which is based on SORIL (Swinging Objective Retarding Immersion Lens) technology (8). The column achieves three design goals for increasing image throughput: 1. A high primary beam current while maintaining high resolution (1.8 nm@1 keV, 4 nA); 2. High signal electron collection efficiency (>95 %); 3. Large available high definition FOV to increase data throughput in each single frame (96 µm FOV with 24k × 24k pixels@4 nm pixel size).

In the SORRIL™ column, the primary electron beam emitted from the electron source maintains a high energy (12 keV) until reaching the objective lens. The primary electron beam is then decelerated and focused by the objective lens fields onto the sample surface with the required landing energy. This ensures that the primary electron energy remains on the optical axis for as long as possible, thereby reducing the Coulomb interaction and associated beam blurring. The column combines electrical retarding fields and magnetic immersion fields in the objective lens to enable high resolution and high flexibility in signal electron detection. The magnetic objective lens creates a magnetic field close above the sample such that the sample is “immersed” in the magnetic field. A retarding electrostatic field for the primary beam is formed between the in-lens BSE detector (BSED) and the sample, which is kept at a high negative voltage. The magnetic field and electrostatic fields are designed to closely overlap, allowing high resolution to be achieved, especially for low landing energies of the primary beam. The BSED has two main roles. The first is as a part of the electrostatic objective lens. The second is that it is used to receive signal electrons. In general, combined immersion magnetic lens and retarding electrostatic lens systems have a much lower spherical and chromatic aberration constant than pure magnetic lens (48) systems, especially for low landing energies (< 3 keV). Based on this column design, the Navigator-100 high-throughput SEM can achieve high beam currents while maintaining high resolution compared to conventional SEM, even at low landing energies. This allows a greatly increased primary electron injection dose, with a resulting benefit of minimizing the pixel dwell time. Combined with the electron detection system, the Navigator-100 high-throughput SEM can achieve a resolution...
of 1.8 nm at large current of 4 nA and low landing energy of 1 keV, with very short pixel dwell time of 60 ns (Fig. S18), much shorter than in a conventional SEM, where the pixel dwell time is typically several thousand nanoseconds.

**Detection system**

The SORRIL™ column is equipped with two annular detectors, positioned on the primary beam axis as shown in Fig. S17. The in-lens BSED, with an inner hole is located of several millimeters, is placed under the pole pieces of the magnetic lens and is a part of electrostatic objective lens. A retarding electrostatic field for the primary beam is formed between the in-lens BSED and the sample stage, which is kept at a negative high voltage bias $V_1$ (-11kV @1keV). The in-column secondary electron detector (SED), with an inner hole as small as a few hundred micrometers, is located above the objective lens. Both the in-column SED and the in-lens BSED are fast diodes, where exciting one electron-hole pair requires a mean energy of $\bar{E}_i = 3.6$ eV (Si). The signal electrons in the strong retarding field, which are accelerated up to more than 11 keV (at 1 keV), resulting in enhancing the amplification factor of the direct electron detector above $\bar{n} = E/\bar{E}_i = 3000$ ($E = 11$ keV). This large amplification is greatly beneficial for achieving a good SNR in the imaging system.

Since the in-lens BSED is located in a retarding electrostatic field and a magnetic field, and as the electrostatic fields and magnetic field of the objective lens are designed to very closely overlap, almost all signal electrons are accelerated and attracted by the strong receiving fields into the objective lens, and then collected by the detection system. BSEs, with wide emission angle not adjacent to the optical axis, are collected by the in-lens BSED placed directly underneath the magnetic lens pole piece. All SEs, as well as a few BSEs perpendicular to sample, pass through the inner hole of the BSE detector and are collected by the in-column SE detector with low loss. The crossover of the SEs is controlled by the receiving field, and is located in the inner hole of the BSE detector. Additionally a control electrode, which forms part of the electrostatic lens, is used to flexibly adjust the field strength to impact the signal electron trajectory. This design of the detection system leads to a collection efficiency of $> 95\%$ at close working distances. Thus, the BSED can deliver compositional contrast while the SED delivers topographic information even at very fast pixel dwell times. The combined objective fields achieve high resolution and high signal
electron collection efficiency simultaneously on both detectors, especially at low primary beam landing energies.

Additionally, in contrast to standard field emission SEMs using a scintillator–photomultiplier detector (electron $\rightarrow$ photon $\rightarrow$ signal), the SED and BSED in SORRIL™ column are both direct fast diode detectors (electron $\rightarrow$ signal directly). These specially designed detectors ensure minimum stray capacitance and enable detector rise-times down to less than 10 ns, at an amplification factor of $10^4$ V/A. The narrow bandwidth of the detectors combine with the electron optical and detection system to achieve high imaging rate, with as low as 10 ns pixel dwell time, cutting half time compared with the diode detector module (49). The very short pixel dwell time of 10 ns allows the Navigator-100 high-throughput SEM achieve television (TV) speed imaging for use as a video camera. For example, in video mode, one $512 \times 512$ pixels image takes only 6 ms per frame, meaning dynamic recording at 150 fps is possible.

Figure S19 shows simultaneously recorded single frames of SED and BSED high definition images (each $24k \times 24k$ pixels) taken from a region of a lithium battery cathode sample, using the minimum dwell time of 10 ns, with a total image collection time for both images of just 6.5 s. Even under this condition the composition and topography of the sample surface are clearly recognizable.

**Deflection system**

The SORRIL™ column combines a focusing lens system and an in-lens deflection system as a swinging objective lens (SOL). The SOL is one type of variable axis lens system developed in e-beam lithography to solve the problem of sharply decreasing resolution with large increases in the FOV. An in-lens electrostatic deflector is placed close to the pole piece of the magnetic lens and mixed into the combined magnetic and electrostatic fields. Under an appropriate relationship between the deflective field and the objective (defined by the SOL condition ($50, 51$)), the deflecting and focusing fields results in a swinging axis lens acting just like a prism inlaying the lens, with the magnetic field acting to focus the beam and the electrostatic field providing deflection. In combination with an upper deflector system placed away from the lens field, the system can achieve a large FOV with low aberration.
Figure S20 shows a schematic illustration of the SOL, in which optical axis of the focusing lens is swung during scanning. The SOL design results in only small off-axis aberrations at the edge of the FOV, such that minimized distortion and optimized resolution is achieved at the edges and corners of the image, even at a large FOV, and thus improves throughput because of the larger image area that can be collected in each single scanning frame. Furthermore, the larger FOV in each single frame leads to a reduced stage movement overhead when observing large sample areas.

In order to take maximum advantage of the SOL design, all the deflectors used in the SORRIL™ column are electrostatic. Electrostatic deflectors exhibit much less hysteresis and much lower eddy current errors than their magnetic counterparts, and can be manufactured more precisely. These advantages result in electrostatic deflector scanning with high speed and only small edge aberrations.

With the SOL system, the Navigator-100 high-throughput SEM can achieve a large FOV with low distortions and small edge aberrations in one single frame. Figure S21 shows a 24k × 24k image with a 96 μm FOV at a 4 nm pixel size, collected as one single image frame. Even at the edges of the FOV, the image quality and distortion remain similar to that in the center. Figure S22 shows a montage of two images in sample SA5. The overall distortion of the images (the factor affecting the montage accuracy) accounts for less than 0.1 % of the total number of image pixels. No additional algorithm was used to correct this small distortion during montaging. Each pair of adjacent images was montaged by using template matching and the relative coordinate relationship between them then calculated. According to the relative coordinate relationship, a global coordinate calculation algorithm was designed to reduce errors by using a dichotomy method. Based on the above, the absolute position coordinate for each tile in the final atlas 2D montage was calculated.

Through a series of design features the throughput of a single-beam SEM has been increased up to 2 x 100 MPixels/s, with simultaneous SE and BSE imaging while maintaining nm-scale resolution and good image quality. Compared to multi-beam high throughput SEMs, the capability of this new microscope makes the single beam high throughput SEM ideally suited for cross-scale analysis at high resolution, especially for fast and flexible identification of microstructural information.
Supplementary figures & tables

Fig. S1. Heterogeneity in spatial distribution of carbides in the as-cast sample of the second-generation nickel-base single-crystal superalloy. (A) Multi-scale panorama atlas of the as-cast sample. (B) Enlarged image of the square frame in (A), covering both inter-dendritic and dendritic regions. (a) An inter-dendritic region containing MC carbides; (b) An inter-dendritic region where no carbides are present; (c) A dendritic region (also no carbides).
Fig. S2. Heterogeneity in spatial distribution of carbides in the heat-treated sample of the second-generation nickel-base single-crystal superalloy. (A) Multi-scale panorama atlas of the heat-treated sample. (B) Enlarged image of the square frame in (A), covering both inter-dendritic and dendritic regions. (a) An inter-dendritic region containing both MC and M$_{23}$C$_6$ carbides; (b) An inter-dendritic region where only the matrix is present; (c) A dendritic region containing M$_{23}$C$_6$ carbides. Not all M$_{23}$C$_6$ are visible by etching in this sample, because some are in narrow $\gamma$ channels.
Fig. S3. Heterogeneity in spatial distribution of carbides in the second-generation nickel-base single-crystal superalloy interrupted after 22.2 h creep testing. (A) Multi-scale panorama atlas of the sample after creep for 22.2 h. (B) Enlarged image of the square frame in (A), covering both inter-dendritic and dendritic regions. (a) An inter-dendritic region containing both MC and M$_{23}$C$_6$ carbides; (b) An inter-dendritic region containing M$_{23}$C$_6$ carbides; (c) A dendritic region containing M$_{23}$C$_6$ carbides.
Fig. S4. Heterogeneity in spatial distribution of carbides in the second-generation nickel-base single-crystal superalloy interrupted after 131.6 h creep testing. (A) Multi-scale panorama atlas of sample after creep for 131.6 h. (B) Enlarged image of square frame in (A), covering both inter-dendritic and dendritic regions. (a) An inter-dendritic region containing MC and M$_{23}$C$_6$ carbides; (b) An inter-dendritic region containing M$_{23}$C$_6$ carbides; (c) A dendritic region containing M$_{23}$C$_6$ carbides.
Fig. S5. Heterogeneity in spatial distribution of carbides in the second-generation nickel-base single-crystal superalloy after creep-rupture. (A) Multi-scale panorama atlas of the sample after creep-rupture. (B) Enlarged image of square frame in (A), containing both inter-dendritic and dendritic regions. (a) An inter-dendritic region containing MC and M₂₃C₆ carbides; (b) An inter-dendritic region containing M₂₃C₆ carbides; (c) A dendritic region with M₂₃C₆ carbides.
Fig. S6. Quantitative EDS mapping of inter-dendritic regions in the five samples, showing the composition of MC and M$_{23}$C$_6$ carbides. Only Ta/Hf-rich MC carbides are found in the as-cast sample (SA1). After heat treatment Cr/Re-rich M$_{23}$C$_6$ carbides started to precipitate (see SA2 sample).
Fig. S7. The microstructure of M$_{23}$C$_6$ carbides and surrounding matrix, and their relationship, in inter-dendritic regions. (A) Inter-dendritic region of SA1, $g = [020]$, $B = [100]$. No M$_{23}$C$_6$ carbides are present. (B) Inter-dendritic region of SA2, $g = [11\bar{1}]$, $B = [110]$. Cluster-like M$_{23}$C$_6$ grow and consume adjacent $\gamma$ phase. (C) Inter-dendritic region of SA3, $g = [002]$, $B = [100]$. Cluster-like M$_{23}$C$_6$ grow further and continue to consume adjacent $\gamma$ phase. (D) Inter-dendritic region of SA4, $g = [020]$, $B = [100]$. The morphology of M$_{23}$C$_6$ carbides has become polyhedral and the carbides are now surrounded by $\gamma'$ phase. (E) Inter-dendritic region of SA5, $g = [002]$, $B = [110]$. A high density of dislocations cut into the $\gamma'$ phase but do not cut the M$_{23}$C$_6$ carbides. Scale bars, 0.5 $\mu$m.
Fig. S8. Diffraction patterns of M$_{23}$C$_6$ carbides and their surrounding matrix. (A), (B), (C) Selected area electron diffraction patterns of a M$_{23}$C$_6$ carbide and its surrounding matrix, B = [100], [011] and [111] respectively. Diffraction points connected by green dotted lines belong to the $\gamma$ and $\gamma'$ phase; diffraction points connected by yellow dotted lines belong to the $\gamma'$ phase; diffraction points connected by red dotted lines belong to M$_{23}$C$_6$. Scale bars, 5 nm$^{-1}$. 


**Fig. S9. High-throughput SEM and conventional SEM images of five deep-etched samples.**

(A)-(E), MC and $M_{23}C_6$ carbides in the inter-dendritic and dendritic regions of SA1 (as-cast), SA2 (heat-treated), SA3 (creep after 22.2 h), SA4 (creep after 131.6 h) and SA5 (after creep-rupture) samples (high-throughput SEM using BSE signal at 2 keV landing energy). (a) Inter-dendritic region with MC and $M_{23}C_6$ carbides; (b) Inter-dendritic regions only with $M_{23}C_6$ carbides; (c) Dendritic regions only containing $M_{23}C_6$ carbides. (F) SEM images of the etched SA5 sample (SE signal; 15 kV accelerating voltage). Primary MC carbides provide crack sources in the SA5 sample; yellow arrows point to MC carbides.
Fig. S10. Four typical types of polyhedral $M_{23}C_6$ carbide in the SA5 sample (after creep-rupture). (A)-(D) Schematic diagrams of the four typical polyhedral $M_{23}C_6$ carbides, connected to the matrix by $\{001\}$, $\{1\overline{1}0\}$ and $\{1\overline{1}\overline{1}\}$ $M_{23}C_6/\gamma'$ interfaces. The minimum number of interfaces is 8 and the maximum is 26. (E) High-throughput BSE images of polyhedral $M_{23}C_6$ carbides (2 keV landing energy), corresponding to (A)-(D) respectively. Scale bars, 200 nm.
Fig. S11. Heavy atom occupation of special positions at (001) M$_{23}$C$_6$/γ' interfaces. (A), (D) HAADF images of a (001) M$_{23}$C$_6$/γ' interface viewed along the [100] and [110] zone axes respectively. (B) Atomic intensity profile along the red dotted rectangle in (A). Heavy element atoms occupy positions indicated by the numbers 1 and 2. (C) (001) M$_{23}$C$_6$/γ' atomic interface model viewed along the [100] zone axis. The red spheres are Re atoms, the blue spheres are Cr atoms, the brown spheres are C atoms and the grey spheres are Ni/Al atoms. (E) Atomic intensity profile along the red dotted rectangle in (B). Heavy element atoms occupy positions indicated by the number 3. (F) (001) M$_{23}$C$_6$/γ' atomic interface model viewed along the [110] zone axis. The red spheres are Re atoms, the blue spheres are Cr atoms, the brown spheres are C atoms and the grey spheres are Ni/Al atoms. Heavy atoms exist at positions 1, 2 and 3, while position 3 corresponds to the highest heavy element density.
Fig. S12. Heavy atom occupation of special positions at \{0\{1\} M_{23}C_6/\gamma' interfaces.

(A), (F) HAADF images of a (0\{1\}) M_{23}C_6/\gamma' interface viewed along the [100] zone axis and a (1\{1\}) M_{23}C_6/\gamma' interface viewed along the [110] zone axis. The arrows indicate the direction of three lines profile scans. (C), (D), (E) Atom intensity profiles corresponding to the yellow, blue and red dotted frames in (A). There is a regular distribution of heavy element atoms in the near-interface \gamma' phase region. (B) Atomic model for a (0\{1\}) M_{23}C_6/\gamma' interface viewed along the [100] zone axis. The red spheres are Re atoms, the blue spheres are Cr atoms, the brown spheres are C atoms and the grey spheres are Ni/Al atoms. (H), (I), (J) Atom intensity profiles along the yellow, blue and red dotted frames in (F). No high signal intensity is found at the interface. (G) Atomic model for a (1\{1\}) M_{23}C_6/\gamma' interface viewed along the [110] zone axis. The red spheres are Re atoms, the blue spheres are Cr atoms, the brown spheres are C atoms and the grey spheres are Ni/Al atoms. The reason for no high signal is due to a low density of heavy element atoms at the interface.
Fig. S13. Heavy atom occupation of special positions at (111) $M_{23}C_6/\gamma'$ interfaces. (A) HAADF image of a (111) $M_{23}C_6/\gamma'$ interface viewed along the [110] zone axis. The arrows point out the direction of two line-profile scans. (B) Atom intensity profile along the red dotted frame in (A). A strong intensity is seen at some positions. (C) Atom intensity profile along the yellow dotted frame in (A). No strong profile signal at the interface is seen. (D) Atomic model for a (111) $M_{23}C_6/\gamma'$ interface viewed along the [110] zone axis. The red spheres are Re atoms, the blue spheres are Cr atoms, the brown spheres are C atoms and the grey spheres are Ni/Al atoms. The strong signal seen in (B) is due to a high atomic density, with no heavy atoms located at the interface.
Fig. S14. Creep curves for three samples under conditions of 1038°C/155MPa. The creep curves comprise two creep interrupted samples (after 22.2 h and 131.6 h) and one sample tested to creep rupture (238.4 h).
Fig. S15. Loading direction and cutting orientation of creep specimens. (A) Schematic diagram of the creep testing rod. (B) Schematic projection showing the viewing section orientation of the SEM samples, and TEM/STEM foils
Fig. S16. System components in the Navigator-100 high-throughput SEM. Photo Credit: Shuai Li, Focus e-Beam Technology (Beijing) Company Limited.
Fig. S17. Schematic drawing of the SORRIL™ column and electron trajectories.
Fig. S18. Image of Au on C as a demonstration of achievable resolution. Resolution=1.8 nm, beam current=4 nA, landing energy=1 keV, pixel dwell time=60 ns.
Fig. S19. BSE (left) and SE (right) images of a lithium ion battery cathode. Beam current = 8 nA, landing energy = 2 keV, pixel dwell time = 10 ns, image pixel size = 24k × 24k.
Fig. S20. Schematic of the swinging objective lens.
Fig. S21. Illustration of the large FOV and low edge distortion. It shows the image of a square pattern on a wafer collected as a single frame. FOV = 96 um; beam current = 4 nA, landing energy = 1 keV, pixel dwell time = 10 ns, pixel size = 4 nm, image pixel size = 24k × 24k.
Fig. S22. Example montage of two adjacent BSE images in sample SA5. At the edges of the FOV, the image quality and distortion remain similar to that in the center.
Table S1.
Summary statistics for MC and M₂₃C₆ parameters in the five samples

| Sample                | MC mean size (µm²) | M₂₃C₆ mean size (µm²) | Number of M₂₃C₆ per unit area (mm²) | M₂₃C₆ area fraction (%) | MC area fraction (%) |
|-----------------------|-------------------|-----------------------|-------------------------------------|------------------------|---------------------|
| As-cast               | 1.89              | 0                     | 0                                   | 0                      | 0.247               |
| Heat-treated          | 1.72              | -                     | -                                   | -                      | 0.176               |
| Creep after 22.2 h    | 1.26              | 0.047                 | 37601                               | 0.178                  | 0.164               |
| Creep after 131.6 h   | 1.02              | 0.074                 | 26093                               | 0.194                  | 0.157               |
| After creep-rupture   | 1.03              | 0.135                 | 20001                               | 0.270                  | 0.148               |
Table S2.
Nominal composition of the secondary-generation nickel-base single-crystal superalloy (wt.%)  

|   | C   | Cr  | Co  | W   | Al  | Ta  | Mo  | Hf  | Nb  | Re   | B   | Ni   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|------|
|   | 0.04-0.06 | 6.75 | 7.00 | 4.75 | 6.00 | 6.30 | 1.30 | 0.12 | <0.01 | 2.75 | 0.003-0.005 | Balance |
|   | 7.25 | 8.00 | 5.25 | 6.40 | 6.70 | 1.70 | 0.18 | 3.25 |       |      |      |      |
Table S3.
High-throughput SEM data collection parameters for each of the five examined samples.

| Sample name                      | SA1 (as-cast) | SA2 (heat-treated) | SA3 (creep after 22.2 h) | SA4 (creep after 131.6 h) | SA5 (after creep-rupture) |
|----------------------------------|---------------|--------------------|--------------------------|---------------------------|--------------------------|
| Array-scan region                | 5.55 x 3.62 mm² | 5.49 x 4.83 mm²    | 7.42 x 3.55 mm²          | 9.41 x 3.33 mm²           | 12.96 x 4.33 mm²         |
| Pixel size                       | 35.0 nm       | 15.0 nm            | 15.0 nm                  | 15.0 nm                   | 15.0 nm                  |
| Image size                       | 4k x 4k       | 12k x 12k          | 8k x 8k                  | 8k x 8k                   | 12k x 12k                |
| Tile size                        | 143.4 x 143.4 μm² | 184.3 x 184.3 μm² | 122.9 x 122.9 μm²        | 122.9 x 122.9 μm²         | 184.3 x 184.3 μm²        |
| Scan overlap                     | 10 %          | 10 %               | 10 %                     | 10 %                      | 10 %                     |
| Bit depth                         | 8 bit         | 8 bit              | 8 bit                    | 8 bit                     | 8 bit                    |
| Number of images                 | 1024 (BSE)    | 957 (BSE)          | 2144 (BSE)               | 2550 (BSE)                | 1774 x 2 (BSE & SE)      |
| Total number of pixels (Megapixels) | 17179.9      | 144502.2           | 143881.4                 | 171127.6                  | 535730.1                 |
Movie S1. Multi-scale panoramic atlas
<File added separately>
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