



Influences of Introduced Yttrium Oxide Particles on Superalloy 718

Timothy P. Gabb, Christopher A. Kantzos, Timothy M. Smith, and Henry C. de Groh III
Glenn Research Center, Cleveland, Ohio

Aaron C. Thompson
HX5, LLC, Brook Park, Ohio

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.**
Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.**
Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain

minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.**
Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.**
Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.**
Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.**
English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>



Influences of Introduced Yttrium Oxide Particles on Superalloy 718

Timothy P. Gabb, Christopher A. Kantzos, Timothy M. Smith, and Henry C. de Groh III
Glenn Research Center, Cleveland, Ohio

Aaron C. Thompson
HX5, LLC, Brook Park, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

Dr. Joseph Sims of Quadrus Corp. is recognized for discussions in additively manufacturing some of the test materials. The refined preparations of metallographic sections by Drew J. Davidson at NASA Glenn Research Center are appreciated.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at <https://www.sti.nasa.gov/> and <https://ntrs.nasa.gov/>

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Influences of Introduced Yttrium Oxide Particles on Superalloy 718

Timothy P. Gabb, Christopher A. Kantzos, Timothy M. Smith, and Henry C. de Groh III*

National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Aaron C. Thompson
HX5, LLC
Brook Park, Ohio 44142

Summary

Additive manufacturing has proven useful for introducing oxide particles into superalloys to provide oxide dispersion strengthening (ODS) at high temperatures. The objective of this study was to compare tensile and creep failure modes for additively manufactured superalloy 718, after introducing oxide particles. Fine yttrium oxide (yttria) particles were introduced into 718 powder using two different powder-mixing methods. Additive manufacturing by laser powder bed fusion was then used to prepare specimen blanks for each case, oriented parallel and transverse to the build direction. These were subsequently given consistent stress relief, hot isostatic pressurization, and final heat treatments before being subjected to tensile and creep tests at varied temperatures. Compared to 718 without ODS (“no-ODS”), roll-mixed and acoustic-mixed ODS materials did not show improved tensile strengths at room temperature, 760 °C, or 1093 °C. Parallel to the build direction, the tensile failure strains of roll-mixed ODS material were lowest in these tests. Flattened clumps of yttria had formed transverse to the build direction in roll-mixed material, which were easily cracked. The creep rupture response at 760 °C in the build direction was highest for acoustic-mixed material. Creep tests at 1093 °C showed varied results, with low rupture lives associated with enhanced cavitation at grain boundaries and surface oxidation. Transverse to the build direction, all three materials had low failure strains in tests at 760 °C. The elongated grain boundaries in the build direction failed readily in all transverse specimens tested at 760 and 1093 °C.

Introduction

Additive manufacturing (AM) by laser powder bed fusion (L-PBF) has been commonly applied to produce the widely used commercial superalloy 718 (Refs. 1 and 2). In this technique, a layer of powder is applied at controlled thickness onto a surface or bed and then carefully and specifically melted. This localized melting occurs by translating a laser beam across the layer of powder in a controlled pattern. This repetitive sequence is often performed in inert gas to prevent environmental contamination. Subsequent processing typically includes stress relief, hot isostatic pressurization, and heat treatment as necessary for intended applications. Applications of these advanced AM processes to some nickel-based superalloys have progressed rapidly (Refs. 1 and 2). In select cases, this AM process, subsequent hot isostatic pressurization, heat treatment, and final surface finishing have been scaled up to produce aerospace components (Ref. 3).

*Currently retired.

Oxide dispersion strengthening (ODS) has been shown to improve the creep resistance of some nickel-based superalloys (Ref. 4). Such early ODS superalloys were produced through mechanical alloying of superalloy powder in attritor or rolling mills followed by thermomechanical processing (Refs. 5 to 7). Subsequent consolidation under pressure at high temperature was followed by multiple hot working and heat treatment steps to produce superalloys with a dispersion of oxide strengtheners and grains elongated in the rolling direction to provide superior creep rupture resistance in this direction at high temperatures. Several commercial ODS nickel-based superalloys were developed from this processing method (Ref. 7). More advanced ODS superalloys have been reported in more recent studies (Ref. 8).

AM provides new opportunities to introduce such oxide dispersions to potentially improve the creep resistance of a given superalloy. In one approach, attritor milling was employed to introduce yttrium oxide (yttria, Y_2O_3) powder particles into atomized powder of a model nickel-based superalloy (Ref. 9). In another approach, acoustic mixing has been used to introduce yttria into atomized powder of multiple-principal-element superalloys (Refs. 10 and 11).

The objective of the current study was to compare monotonic failure modes for AM superalloy 718 with and without introduced oxide particles. Monotonic tensile and creep failure responses were assessed for this legacy superalloy with and without the introduced oxide particles. The AM microstructures and prevalent failure modes for each ODS material were considered in contrast to those for comparably processed material without the added oxide dispersion.

Materials and Procedures

Superalloy 718 argon-atomized powder screened to -270 mesh was mixed with 0.6 wt% of yttria powder of 100 to 200 nm diameter using two different approaches. One batch of ODS powder was manufactured by roll mixing, and the metal powder, nanometer-sized oxides (at 0.6 wt%), and mixing media were rolled in a vessel to coat the nanometer-sized yttria onto the metal powder. Acoustic mixing with containers of the combined powders shaken at acoustic frequencies was applied to another batch of powder. Laser powder bed fusion was used to fabricate mechanical test blanks of no-ODS and roll-mixed ODS materials at Quadrus Corp. (Huntsville, AL) using a Concept Laser GmbH M1 laser powder bed fusion system. Acoustic-mixed ODS material was fabricated with an EOS M 100 at NASA Glenn Research Center using a third batch of powder. Each system used process parameters developed specific to the printer and alloy, a steel build plate, and a controlled argon atmosphere containing no greater than 0.12 % O_2 . Specimen blanks were built with centerlines parallel and transverse to the build direction for each material. Hot isostatic pressurization at 1163 °C for 4 h and solution heat treatment at 1066 °C for 1 h, then 760 °C for 10 h, and 649 °C for 20 h were applied to no-ODS and ODS specimen blanks by Bodycote Corp. (Cincinnati, OH).

Tensile tests were performed at Metcut Research Associates (Cincinnati, OH) per ASTM E21-17 (Ref. 12). These tests utilized an axial extensometer and resistance heating furnace at temperatures of 25, 760, and 1093 °C. The tests were performed at a displacement rate producing a strain rate of approximately 0.5 %/min to reach 2% strain. Tests were then continued to fracture at a faster displacement rate giving a strain rate of approximately 5 %/min. Constant-load creep rupture tests were also performed by Metcut, per ASTM E139-11 (Ref. 13). A lever arm system applied axial load with an axial extensometer and resistance heating furnace in tests at temperatures of 760 and 1093 °C.

Microstructures were examined from specimens metallographically prepared parallel and transverse to the additive build direction. Samples were polished using SiC grit polishing paper followed by 0.05- μm colloidal silica vibratory finishing. Optical and scanning electron microscopy were employed to examine

grain microstructures. A Keyence VHX-V1 optical microscope was used to acquire optical images. Line intercept methods were used for measuring average grain size. A Tescan MAIA3 field emission scanning electron microscope (SEM) operated at 15 kV and 15 μ A with an integrated Oxford energy dispersive spectroscopy (EDS) system was then employed. Electron backscatter diffraction (EBSD) data gathered on this system were analyzed using integrated Aztec software. Fracture surfaces were examined using optical microscopy and Jeol 6400 and IT710HR SEM on fracture surfaces, as well as metallographic sections of these surfaces prepared parallel to the loading direction.

Results

Composition and Microstructure

Average compositions of fully processed specimen sections in weight percent as measured by NSL Analytical Services (Cleveland, OH) using an Optima 5300 inductively coupled plasma mass spectrometer and a LECO combustion analyzer are compared in Table 1 for the three materials. Table 2 shows comparable average compositions in weight percent for roll-mixed and acoustic-mixed ODS AM materials, as measured on relatively large yttria particles over 1 μ m in width by EDS-SEM. Typical grain structures normal and parallel to the loading direction for specimens aligned in the build direction are shown in Figures 1 and 2. Sections normal to the build direction are compared in Figure 1(a). In these sections, no-ODS materials showed equiaxed grains measuring 50 μ m in average width with random texture. Roll-mixed ODS material had a bimodal grain structure. Large equiaxed grains of 66 μ m average width were surrounded by smaller grains at 9 μ m average width. Acoustic-mixed ODS material had small equiaxed grains of 10 μ m average width transverse to the build direction; these were later found to be elongated nearly 10 times in the build direction.

Sections parallel to the build direction are compared in Figure 2. In these sections, no-ODS material had equiaxed grains without significant crystallographic texture measured in the microstructure. For the roll-mixed material, the finer grains are elongated in the build direction, and these grains tended to be aligned with the [001] crystallographic axis near their elongated direction. Acoustic-mixed ODS material had small grains of 10 μ m average width that were elongated nearly 10 times in the build direction, and these grains tended to be oriented with the [001] crystallographic axis near their elongated direction.

Failure Responses

Tensile Response

Tensile test results are compared in Table 3, from which ultimate tensile strengths and failure strains are compared in Figure 3. Yttria powder introduced by roll-mixing and acoustic-mixing did not give improved strength over no-ODS material at the tested temperatures for specimens loaded in the build direction or transverse to the build direction. Failure strains showed more significant variations among materials, suggesting differences in failure mode. In the build direction, the roll-mixed material had the lowest failure strain for each tested temperature, as low as 1.1% at 760 °C. Transverse to the build direction, no-ODS material had the highest failure strains at room temperature and 1093 °C; however, all three materials had low failure strains below 6% at 760 °C.

Tensile fractures for specimens loaded parallel to the build direction are compared for no-ODS, roll-mixed, and acoustic-mixed materials in Figures 4 to 6. At room temperature (Fig. 4), acoustic-mixed material had the highest failure strain and reduction in area, and this was associated with a ductile cup-cone failure having microvoid coalescence within grains at the core and transgranular shear at the surface rim. No-ODS material had this general failure mode, although with segmentation of the shear lips and

lower failure strain. Roll-mixed material had some of these features with the addition of curious flat localized stepped failures. These steps were generally flat, but they were not crystallographic failures. These trends continued for specimens tested at 760 °C in the build direction, as shown in Figure 5. However, several intergranular (IG) cracks also were observed extending from the surface for no-ODS and roll-mixed materials. The flat steps of roll-mixed materials were more numerous at this test temperature, where this material had lowest failure strains. At 1093 °C, surface IG cracks occurred for all three materials, as shown in Figure 6. The flat steps of roll-mixed material now showed bright flakes within. The bright contrast of these flakes in the back-scattered electron micrographs was indicative of a higher average atomic number for the flakes than for the surrounding superalloy.

Typical surfaces of tensile fractures for specimens loaded transverse to the build direction are compared in Figures 7 to 9. For fractures at room temperature, all three materials shown in Figure 7 had ductile failures with segmented cup-cone regions as described above. Transgranular microvoid coalescence was widespread, while scattered grains also had some areas of crystallographic shearing. The fractures at 760 °C shown in Figure 8 had a distinctly different failure mode. Grain boundaries normal to the loading axis failed, producing cracks of unusual profiles. Instead of typical semicircular crack profiles (Ref. 14), these cracks often grew far deeper than their widths. Examination at higher magnifications disclosed the cracks grew preferentially in the same direction in which the grains and their boundaries were elongated, which corresponded to the build direction. Only some failed grains in the no-ODS material were visible that were elongated up to 2 times in the build direction. Failure progression also extended in the build direction. The roll- and acoustic-mixed materials had progressively higher proportions of grains exposed that extended 3 to 10 times in the build direction, aligning with deeper cracks in this same direction. The low failure strains for all three materials in these test conditions were associated with this failure mode. The fractures at 1093 °C shown in Figure 9 also had this directional IG failure mode. The acoustic-mixed material had the most elongated grain boundaries exposed, with corresponding deepest surface cracks and lowest failure strain.

Longitudinal sections were metallographically polished parallel to the loading direction for each tensile test condition to further assess the described failure modes. The sections for roll-mixed specimens tested at 760 °C are shown in Figure 10. Flat steps were apparent for some surface cracks and as separate internal cracks of the specimen fractured in the build direction. Evaluation in the SEM using EDS maps indicate these flat steps were lined with yttria. The specimen that was fractured transverse to the build direction (shown in Fig. 10(b)) had failed along the elongated grain boundaries, and several flat internal cracks were uncovered that were oriented parallel to the loading direction. Evaluations indicated that these cracks also were lined with yttria. This implies flattened clumps of yttria were formed normal to the build direction for roll-mixed material, and these clumps readily cracked during tensile loading.

Creep Rupture Response

Creep rupture results for all tests are listed in Table 4. Rupture lives and failure strains are compared in Figure 11 for specimens aligned in the build direction as well as transverse to the build direction. Material in the build direction with acoustic-mixed yttria had improved rupture response at 760 °C compared with that of roll-mixed and no-ODS materials. Rupture life and failure strains were 5 to 10 times those of roll-mixed material, and these also significantly exceeded those of no-ODS materials. However, for tests at 760 °C transverse to the build direction, no-ODS material had higher rupture responses than acoustic- and roll-mixed ODS materials. Here, failure strains were limited for all to no more than 4%. These materials had intermixed rupture responses at 1093 °C with far lower lives and no clear ranking.

Creep rupture fractures for specimens loaded in the build direction are compared in Figures 12 and 13. IG failure progressed both from the specimen surface and internally for all three materials. Acoustic-mixed material showed more ductile texture on grain boundaries than did the other materials. Roll-mixed fractures again displayed several flat step failures with bright yttria flakes visible inside. At 1093 °C, oxidation rapidly progressed, with oxide layer depths of 30 to 70 µm along the surface and nodules at exposed fracture peaks in the presented tests, lasting just 7.7 to 32.7 h before rupture.

Transverse to the build direction, extended regions of failure along transverse grain boundaries again extended preferentially in the build direction into the specimens, as shown in Figures 14 and 15. This was most prominent at 760 °C for ODS specimens having more elongated grain boundaries, and less so for no-ODS material having near-equiaxed grains. At 1093 °C, oxidation was also evident along the surface and nodules at exposed fracture peaks.

Longitudinal sections were metallographically prepared parallel to the loading direction of these creep rupture specimens, for each specimen orientation and test temperature, to further evaluate the failure modes. Sections from specimens tested in the build direction are compared from tests at 760 and 1093 °C in Figure 16. At 760 °C, numerous narrow cracks at grain boundaries were uncovered at the surface and interior for no-ODS and roll-mixed specimens, but were rare for acoustic-mixed material. Grain boundary cavities and more widely opened cracks were widespread for all tests at 1093 °C. Significant oxidation was also present for all these materials at short rupture lives of 7.7 to 32.7 h along the specimen surface and within cracks at the surface.

Discussion

Introduction of fine yttria particles into 718 powder using roll mixing and acoustic mixing before additive manufacturing (AM) and thermal processing resulted in different oxide distributions, grain microstructures, and mechanical properties. Fine yttria particles were observed in ODS materials after both mixing methods, though flattened clumps of yttria were uncovered in roll-mixed—but not acoustic-mixed—materials. It is possible that yttria powder was more uniformly distributed using acoustic mixing of the powder before AM. Comparative tests of these powder mixtures to perhaps optimize this distribution were not included, and these could be considered in future studies.

The variations of resulting grain microstructures for the three materials after the same thermal treatments was not fully anticipated. Even though using the same baseline 718 hot isostatic pressurization and heat treatment conditions was a reasonable starting point for all three 718 variants, it was not successful in producing consistent grain microstructures. Comparisons of other superalloys have shown differences in grain size response after only the introduction of fine yttria powder (Ref. 11). This has been related to the potential for such oxides to pin grain boundaries after consolidation, preventing recrystallization. This could also be related in part to the use of different AM machines and condition settings, producing different melt pool geometries. No-ODS and roll-mixed ODS materials were both produced on a Concept Laser M1 machine, and the acoustic-mixed ODS material had been produced on a smaller EOS M100. Evidently, modification of AM parameters, hot isostatic pressurization, and heat treatment conditions may be necessary to attain targeted resulting grain size distributions for best comparing creep resistance between ODS and no-ODS materials.

All of the above differences in microstructures for the materials needed to be considered when comparing the mechanical test results and failure modes, rather than just the presence or absence of fine yttria particles. Here, several trends stood out. Testing indicated roll mixing gave lower performance in tensile and creep properties. Two factors can help explain these deficiencies. The resulting flattened clumps of yttria extending roughly 100 µm lying normal to the build direction were clearly weak points

that preferentially failed, especially when tensile loading was applied in the build direction. The flat yttria clumps also showed signs of cracking in creep tests of these specimens and also when loads were applied transverse to the build direction. The boundaries of large grains were also observed to be sites of preferential cracking normal to the load in creep specimens. Modifications of the roll-mixing process and thermal treatments after consolidation could help address these features and associated failure modes. Acoustic-mixed material did not have these detrimental features. This material also had higher failure strains than roll-mixed material during tensile and creep loading, yet an improvement in rupture response over roll-mixed and no-ODS materials was only observed in the build direction at 760 °C.

For creep rupture tests performed at 1093 °C, it was apparent that two other damage processes became enhanced for all three materials. Creep cavities formed at grain boundaries throughout specimen cross sections, whereas surface oxidation layers grew along the surface and even on the fracture surface. It was clear that the introduced yttria did not prevent these damage modes, apparently inherent for the alloy 718 composition. This is a reasonable result, as the composition of superalloy 718 was not optimized for cavitation and oxidation resistance at temperatures near 1093 °C. While some have reported the addition of yttria in superalloys improved oxidation resistance (Ref. 7), such an improvement was not apparent in the present study for superalloy 718.

Low ductility as well as fatigue properties for AM superalloy 718 transverse to the build direction has been reported by others (Ref. 15). The additions of yttria in the present study did not change this response. Instead, these reductions appeared related to the extent of directional growth in grains along the build direction. Such reductions of properties transverse to elongated grains were also reported for early ODS superalloys where directional coarsening was induced by thermomechanical processing (Refs. 4 to 7). It would appear that the benefits of such elongated grains to creep resistance continue to come at the cost of reductions in the transverse direction. Perhaps varied additions of boron at low levels could be screened for improving rupture response in the transverse direction, as previously observed in a directionally solidified γ' -strengthened superalloy (Ref. 16).

Summary and Conclusions

Fine yttria powder was combined with superalloy 718 powder using roll mixing and acoustic mixing. Fine yttria particles were confirmed to be present in both materials manufactured by laser powder bed fusion. However, yttria dispersion differed markedly between these two ODS materials, and grain microstructures varied for these as well as for the baseline material that contained no yttria (no-ODS). Consistent subsequent processing and testing indicated the roll-mixed material had lower performance in tensile and creep properties. Acoustic-mixed material had better performance, but the only consistent improvement over no-ODS baseline was for creep response in the build direction at 760 °C.

Several conclusions are clear from this evaluation:

1. Additive manufacturing (AM) by laser powder bed fusion and the applied thermal treatment paths on 718 can present challenges to attaining suitable grain size and yttria distributions for mechanical property comparison between ODS and no-ODS materials.
2. Roll mixing of fine yttria particles can be especially difficult, with issues to address concerning grain size distribution and yttria dispersion.
3. Oxide-dispersion strengthening via AM could be further developed from tailored mixing of oxide powder, AM conditions, and subsequent hot isostatic pressurization and heat treatments.
4. In the present case, cavitation at grain boundaries and oxidation during creep near 1093 °C may still not be improved with such enhanced ODS processing for this superalloy.

References

1. W.E. Frazier, "Metal Additive Manufacturing: A Review," J. of Mat. Eng. and Perf., V. 23, No. 6 (2014) pp. 1917-1928.
2. W.J. Sames, F.A. List, S. Pannala, R.R. Dehoff, S.S. Babu, "The Metallurgy and Processing Science of Metal Additive Manufacturing," International Materials Reviews, V. 61(5), 2016, pp. 315-360.
3. V. Navrotsky, S. Piegert, O. Andersson, Andreas Graichen, P. Avdovic, "Industrialization and Current Field Experience of Additively Manufactured Gas Turbine Components," Proc. 9th Int. Gas Turbine Conf., Brussels, Belgium, 2018, 47-IGTC18, pp. 1-9.
4. J. Lin, O.D. Sherby, "Creep of Oxide Dispersion Strengthened Materials (With Special Reference to T.D. Nichrome)," NASA CR-135432, Washington, D.C., 1978.
5. R.C. Benn, "Alloy Development of Oxide Dispersion Strengthened High Volume γ' Nickel-Base Superalloys Made by Mechanical Alloys," NADC-78096-60, Naval Air Development Center, Washington, D.C., 1979.
6. T.K. Glasgow, "An Oxide Dispersion Strengthened Alloy for Gas Turbine Blades," Proc. of 20th Structural Dynamics, and Materials Conference, 1979, pp. 249-255.
7. J.J. deBarbadillo, J.J. Fischer, "Dispersion-Strengthened Nickel-Base and Iron-Base Alloys," ASM Handbook, V. 2, 1990, pp. 943-949.
8. M.V. Nathal, "Advanced Turbine Airfoil Development Strategies: Harvesting Low-Hanging Fruit," Advanced Materials & Processes, V. 5, 2015, pp. 21-24.
9. J. Zbiral, "Tensile Properties of Mechanically Alloyed/Milled ODS-Ni-Based Alloys," Met. Trans. A, V. 27A, 1996, pp. 1371-1377.
10. T.M. Smith, A.C. Thompson, T.P. Gabb, C.L. Bowman, C.A. Kantzos, "Efficient Production of a High-Performance Dispersion Strengthened, Multi-Principal Element Alloy", Scientific Reports, V. 10, No. 1, 2020, pp. 9663-9672.
11. T.M. Smith, C.A. Kantzos, N.A. Zarkevich, B.J. Harder, M. Heczko, P.R. Gradl, A.C. Thompson, M.J. Mills, T.P. Gabb, J. W. Lawson, "GRX-810: A 3D Printable Alloy Designed for Extreme Environments," Nature, Vol. 617, 2023, pp. 513-518.
12. ASTM E21-17 "Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials," American Society for Testing Materials, West Conshohocken, PA, 2019.
13. ASTM E139-11(2018) "Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials," American Society for Testing Materials, West Conshohocken, PA, 2018.
14. R.G. Forman, V. Shivakumar, "Growth Behavior of Surface Cracks in the Circumferential Plane of Solid and Hollow Cylinders," Fracture Mechanics: Seventeenth Volume, STP905-EB, ed. J.H. Underwood, R. Chait, C.W. Smith, D.P. Wilhem, W.R. Andrews, J.C. Newman, ASTM International, 1986.
15. M.M. Kirka, A. Plotkowski, P. Nandwana, A. Chaudhary, S.S. Babu, R.R. Dehoff. "Progress in the Processing and Understanding of Alloy 718 Fabricated Through Powder Bed Additive Manufacturing Processes," Proceedings of the 9th International Symposium on Superalloy 718 & Derivatives: Energy, Aerospace, and Industrial Applications, ed. E. Ott, X. Liu, J. Andersson, Z. Bi, K. Bockenstedt, I. Dempster, J. Groh, K. Heck, P. Jablonski, M. Kaplan, D. Nagahama, C. Sudbrack, The Minerals, Metals & Materials Society, Warrendale, PA, 2018, pp. 69-88.
16. B.C. Yan, J. Zhang, L.H. Lou, "Effect of Boron Additions on the Microstructure and Transverse Properties of a Directionally Solidified Superalloy," Mat. Sci. Eng. A, V. 474, 2008, pp. 39-47.

Table 1. Average compositions of fully processed specimen sections^a

Weight %	Al	C	Co	Cr	Fe	Mn	Mo	Nb	O	Si	Ta	Ti	Y	Ni
No-ODS 718	0.47	0.024	0.014	18.47	18.27	0.045	3.22	5.32	0.018	0.048	0.004	0.99	<0.001	Bal.
Roll-mixed	0.46	0.008	0.012	18.32	18.86	0.005	3.18	5.38	0.021	0.012	0.005	0.90	0.13	Bal.
Acoustic-mixed	0.48	0.023	0.036	18.54	19.04	0.013	3.11	5.10	0.030	0.020	0.010	0.85	0.18	Bal.

^aMeasured using inductively coupled plasma mass spectrometer and combustion furnace.

Table 2. Average compositions of yttria particles over 1 μm in width in AM ODS superalloy 718^a

Weight %	Y	O
Roll-mixed material	80.0	20.0
Acoustic-mixed material	80.4	19.6

^aMeasured by EDS-SEM for roll-mixed and acoustic-mixed AM materials.

Table 3. Tensile test results for all materials

Material	Loading axis	Temperature, °C	Yield strength (0.02% offset), MPa	Ultimate strength, MPa	Failure strain, %	Reduction in area, %
No-ODS	Build direction	24	1,179	1,382	13	18
No-ODS	Build direction	760	783	849	4	9.5
No-ODS	Build direction	760	765	829	4.7	8.0
No-ODS	Build direction	1,093	37	61	38.0	30.0
No-ODS	Build direction	1,093	38	60	39.0	32.0
No-ODS	Transverse	24	1,220	1,440	19	32
No-ODS	Transverse	760	793	866	4	6
No-ODS	Transverse	760	779	861	4.1	7.0
No-ODS	Transverse	1,093	32	61	27.0	22.0
No-ODS	Transverse	1,093	39	62	28.0	25.0
Roll-mixed	Build direction	24	1,222	1,340	4.5	9.5
Roll-mixed	Build direction	760	696	738	1.1	4.3
Roll-mixed	Build direction	760	686	758	1.34	3.1
Roll-mixed	Build direction	1,093	45	68	10.2	11.4
Roll-mixed	Build direction	1,093	43	66	11.2	10.3
Roll-mixed	Transverse	24	1,180	1,486	13.8	14.5
Roll-mixed	Transverse	760	745	841	2.4	5.6
Roll-mixed	Transverse	760	752	848	3.0	6.1
Roll-mixed	Transverse	1,093	42	65	11.8	11.2
Roll-mixed	Transverse	1,093	42	65	11.8	10.5
Acoustic-mixed	Build direction	24	1,177	1,312	16.2	44.5
Acoustic-mixed	Build direction	760	652	731	22.8	56.5
Acoustic-mixed	Build direction	760	655	731	28.3	56.8
Acoustic-mixed	Build direction	1,093	54	80	20.8	21.3
Acoustic-mixed	Build direction	1,093	57	79	23.6	20.9
Acoustic-mixed	Transverse	24	1,284	1,440	12.5	24.3
Acoustic-mixed	Transverse	760	672	765	5.4	-----
Acoustic-mixed	Transverse	760	676	772	4.1	6.9
Acoustic-mixed	Transverse	1,093	41	65	6.0	5.3
Acoustic-mixed	Transverse	1,093	41	66	7.5	5.8

Table 4. Creep test results for all materials

Material	Loading axis	Temperature, °C	Stress, MPa	Time, h to % total creep						Rupture life, h	Failure strain, %	Reduction in area, %
				0.1%	0.2%	0.5%	1%	2%	5%			
No-ODS	Build direction	760	324	27.9	121.0	-----	-----	-----	-----	140.0	0.5	-----
No-ODS	Build direction	760	138	-----	-----	-----	-----	-----	-----	426.0	4.1	7.1
No-ODS	Build direction	1,093	21	0.1	0.3	0.9	2.2	5.0	13.5	23.7	12.6	11.3
No-ODS	Build direction	1,093	18	0.4	0.9	2.7	5.8	12.0	28.1	51.2	14.3	12.8
No-ODS	Transverse	760	324	57.9	108.0	144.0	164.0	180.0	-----	191.0	4.1	8.6
No-ODS	Transverse	760	138	-----	-----	-----	-----	-----	-----	425.0	3.9	3.6
No-ODS	Transverse	1,093	21	0.1	0.2	0.7	1.2	5.3	15.5	33.3	12.4	10.9
No-ODS	Transverse	1,093	18	0.6	0.9	2.6	5.8	11.5	26.1	37.5	9.6	9.5
Roll-mixed	Build direction	760	193	5.4	23.0	73.8	110.0	-----	-----	118.0	1.5	-----
Roll-mixed	Build direction	760	159	141.0	175.0	231.0	273.0	-----	-----	285.0	1.4	2.3
Roll-mixed	Build direction	1,093	41	0.0	0.0	0.0	0.1	0.1	0.3	0.4	7.3	11.7
Roll-mixed	Build direction	1,093	31	0.0	0.1	0.1	0.3	0.6	1.3	1.6	7.3	7.9
Roll-mixed	Build direction	1,093	21	0.1	0.2	0.7	1.5	3.0	5.8	7.7	13.7	-----
Roll-mixed	Transverse	760	193	7.4	27.2	63.4	-----	-----	-----	75.1	0.8	-----
Roll-mixed	Transverse	760	159	63.2	104.0	168.0	-----	-----	-----	213.0	0.9	1.0
Roll-mixed	Transverse	1,093	41	0.0	0.0	0.0	0.1	0.1	0.2	0.3	8.3	9.9
Roll-mixed	Transverse	1,093	31	0.0	0.0	0.1	0.2	0.3	0.7	0.9	6.8	8.7
Roll-mixed	Transverse	1,093	21	0.1	0.1	0.3	0.8	1.5	3.1	4.0	9.9	-----
Acoustic-mixed	Build direction	760	193	193.1	23.2	84.2	172.5	233.1	308.1	587.8	----	-----
Acoustic-mixed	Build direction	760	159	74.6	174.0	288.0	400.0	651.0	1,332.0	2,276.0	23.1	29.3
Acoustic-mixed	Build direction	760	159	81.1	171.0	293.0	409.0	631.0	1,276.0	2,123.0	19.1	29.8
Acoustic-mixed	Build direction	1,093	31	0.0	0.1	0.2	0.5	1.2	2.8	4.8	12.9	12.6
Acoustic-mixed	Build direction	1,093	31	0.0	0.0	0.1	0.2	0.3	0.7	0.9	8.5	12.5
Acoustic-mixed	Build direction	1,093	21	0.1	0.4	1.2	2.5	5.3	13.0	32.7	27.3	15.4
Acoustic-mixed	Transverse	760	193	2.1	8.4	47.3	96.2	-----	-----	133.2	2.0	1.1
Acoustic-mixed	Transverse	760	159	2.0	8.0	50.8	138.0	245.0	-----	297.0	3.1	1.6
Acoustic-mixed	Transverse	760	159	1.4	5.7	24.4	46.9	75.3	-----	101.0	4.1	2.7
Acoustic-mixed	Transverse	1,093	31	0.0	0.0	0.1	0.2	0.5	0.8	0.9	7.3	11.5
Acoustic-mixed	Transverse	1,093	21	0.0	0.0	0.1	0.2	0.5	1.1	1.6	11.8	8.7
Acoustic-mixed	Transverse	1,093	7	0.2	0.4	1.4	3.3	8.0	24.6	138.0	29.5	-----

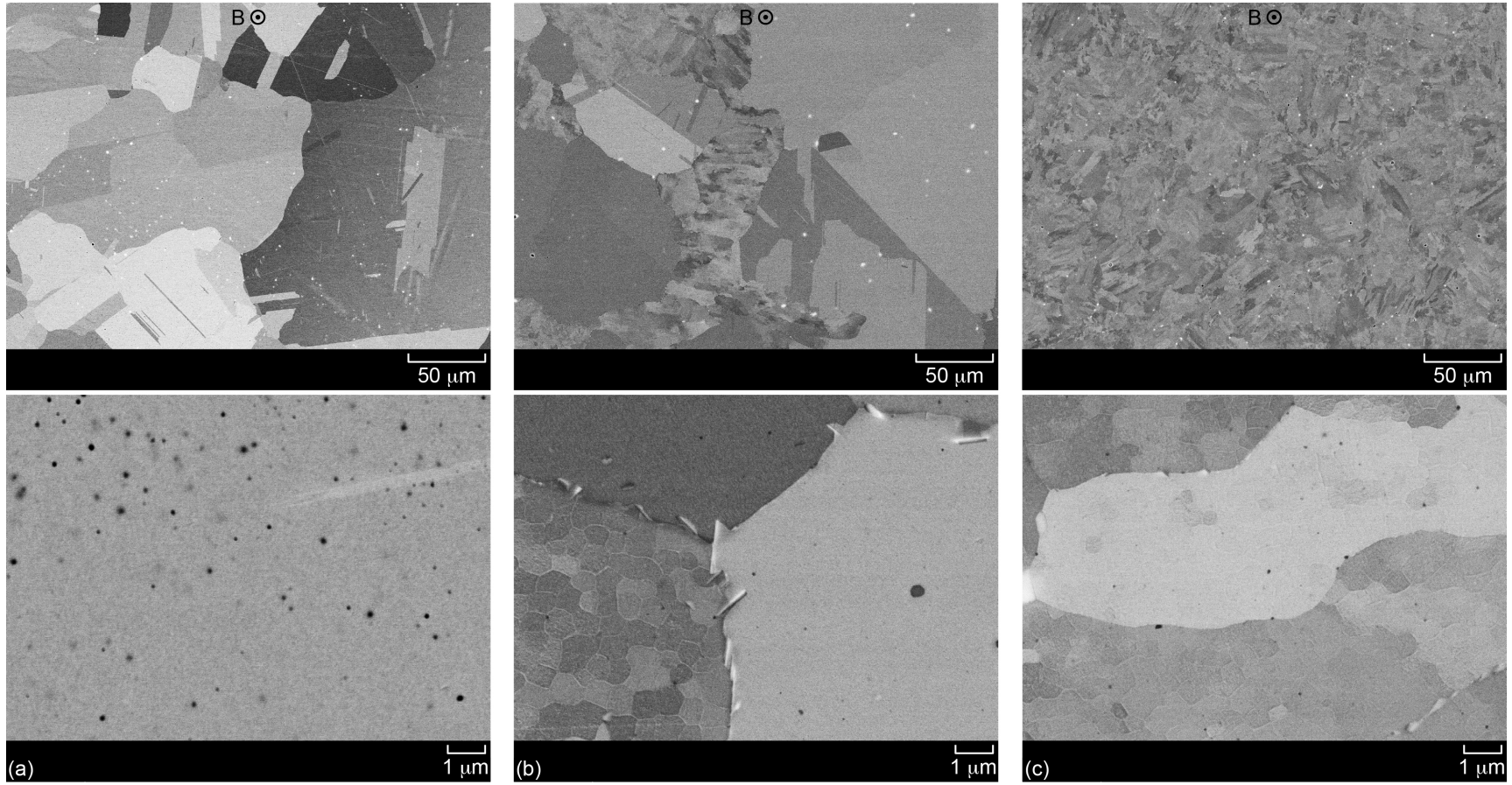


Figure 1. SEM images of transverse sections from tensile specimens aligned in build direction B. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

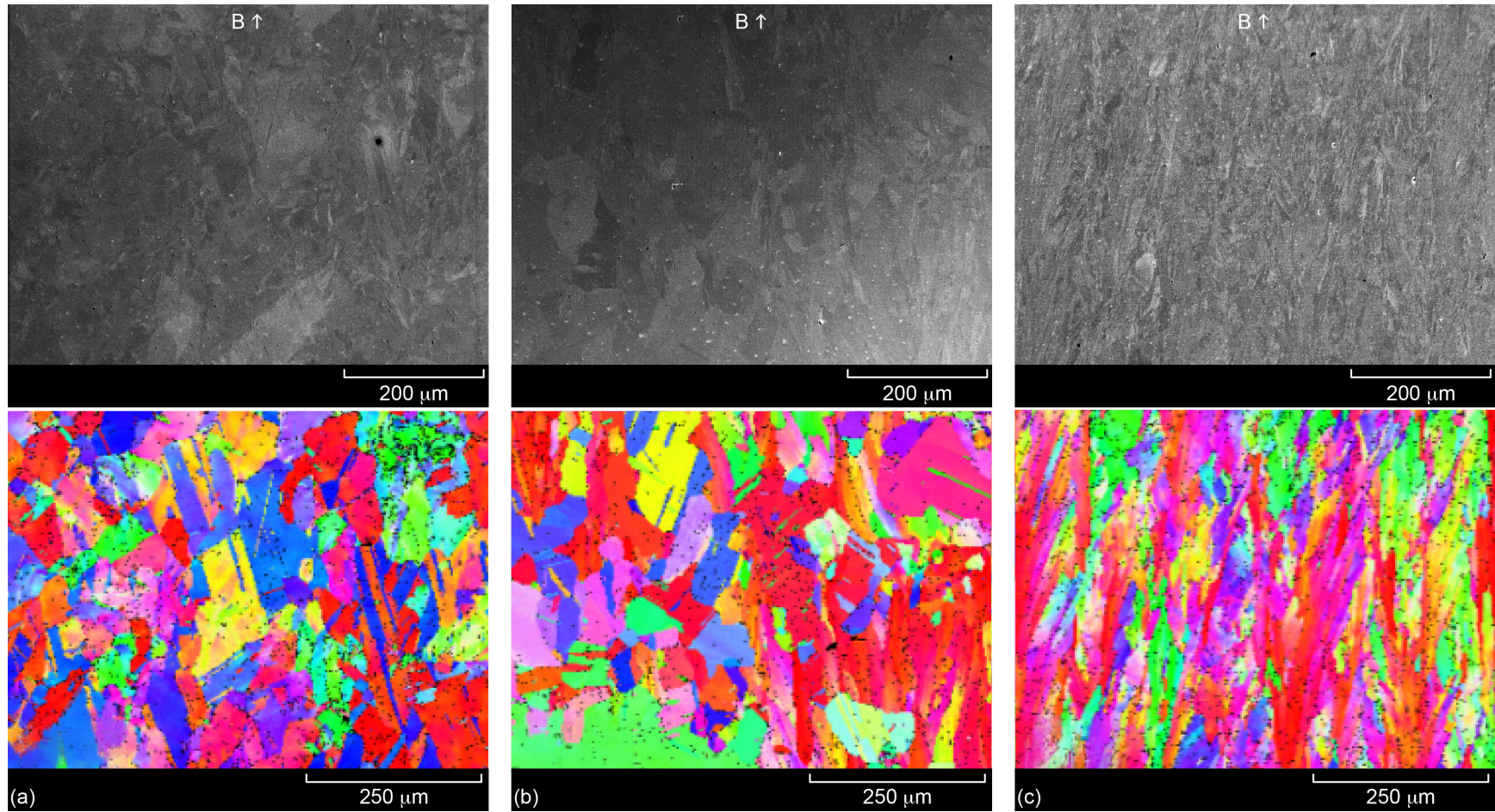


Figure 2. SEM image and corresponding EBSD map of longitudinal sections from tensile specimens aligned in build direction B. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

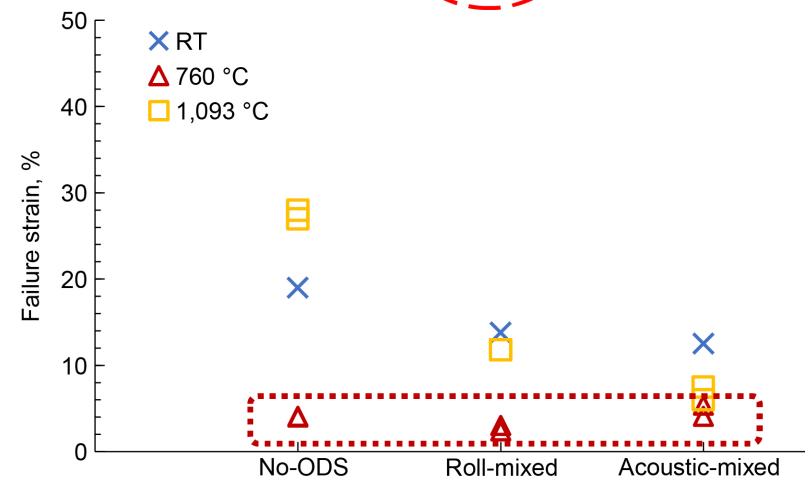
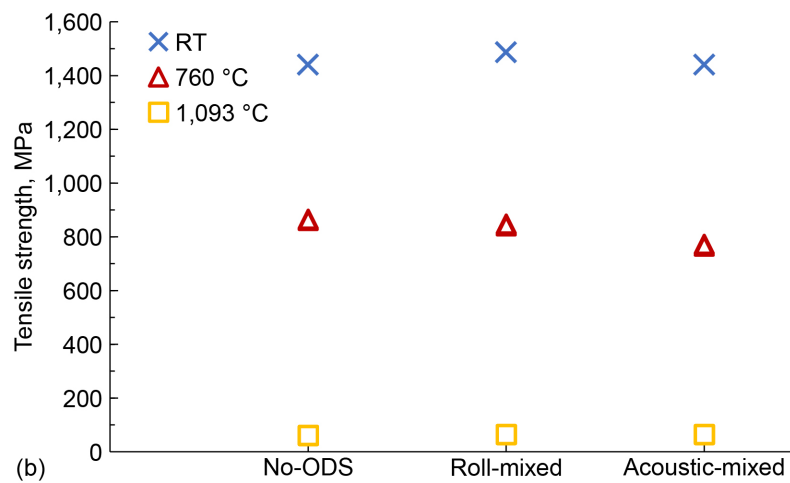
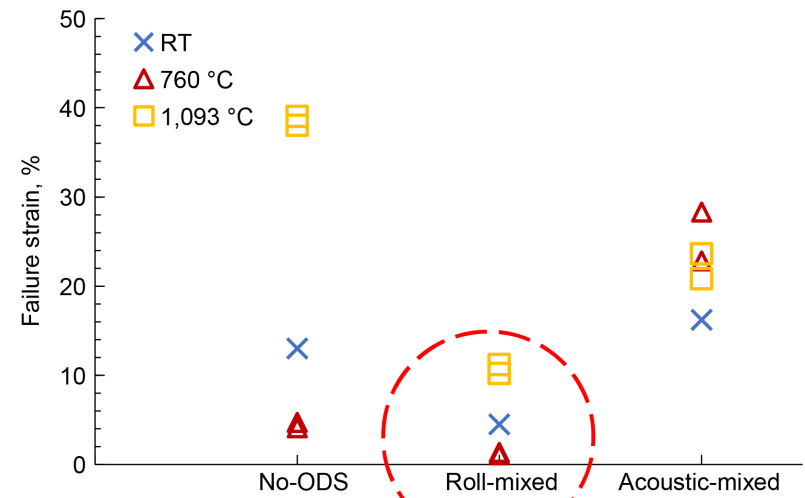
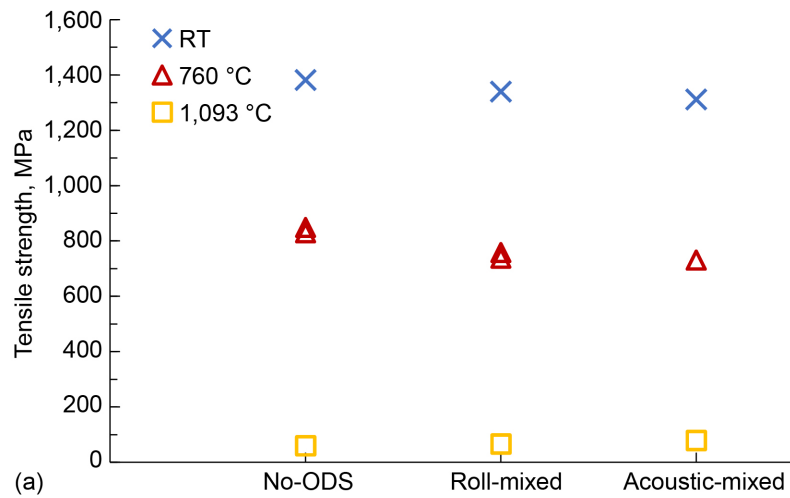


Figure 3. Tensile strengths and failure strains for specimens at room temperature (RT), 760 °C, and 1093 °C. (a) Aligned in build direction. (b) Aligned transverse to build direction.

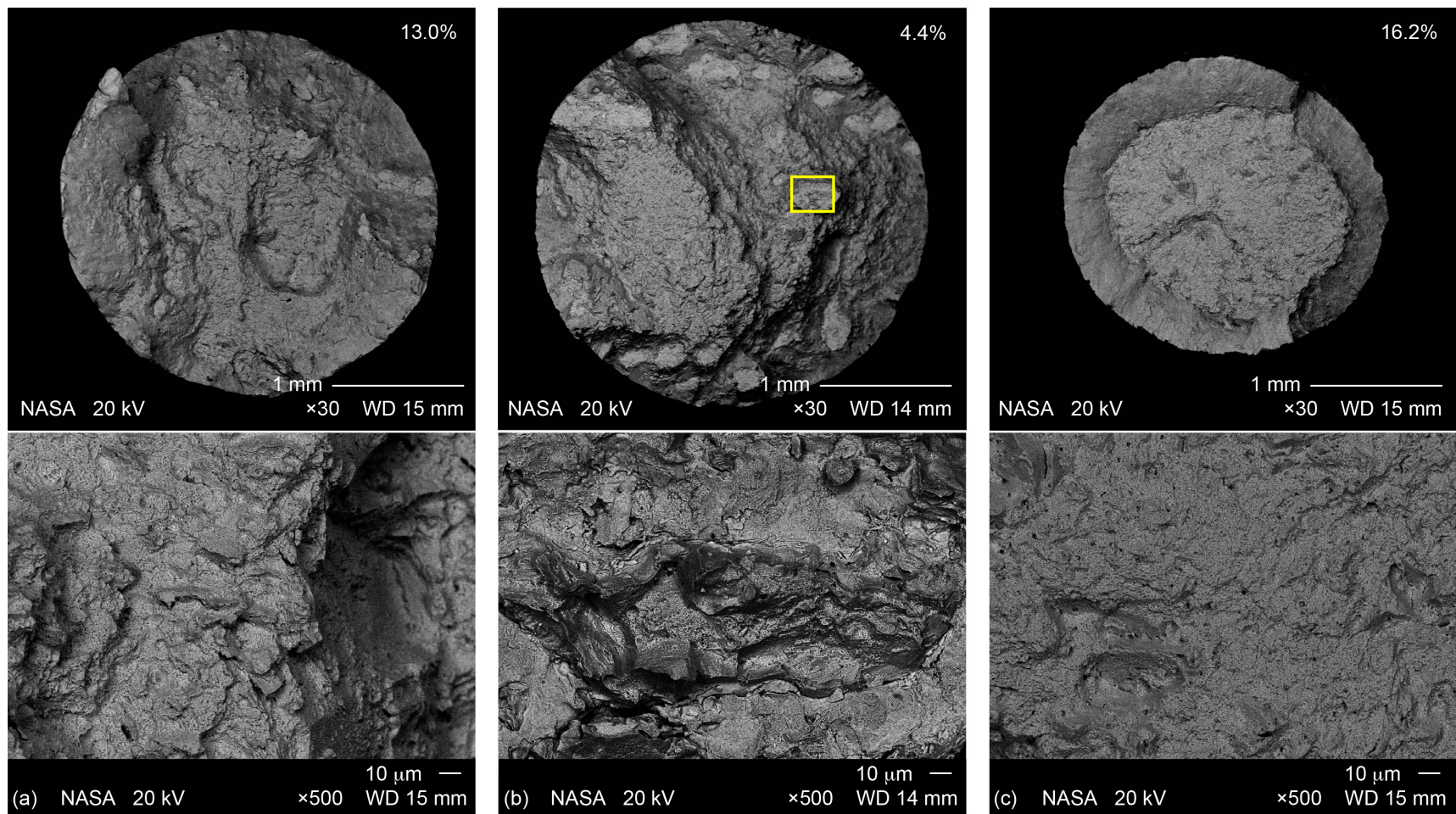


Figure 4. Tensile fractures at 25 °C for specimen oriented in build direction. Failure strains are indicated at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

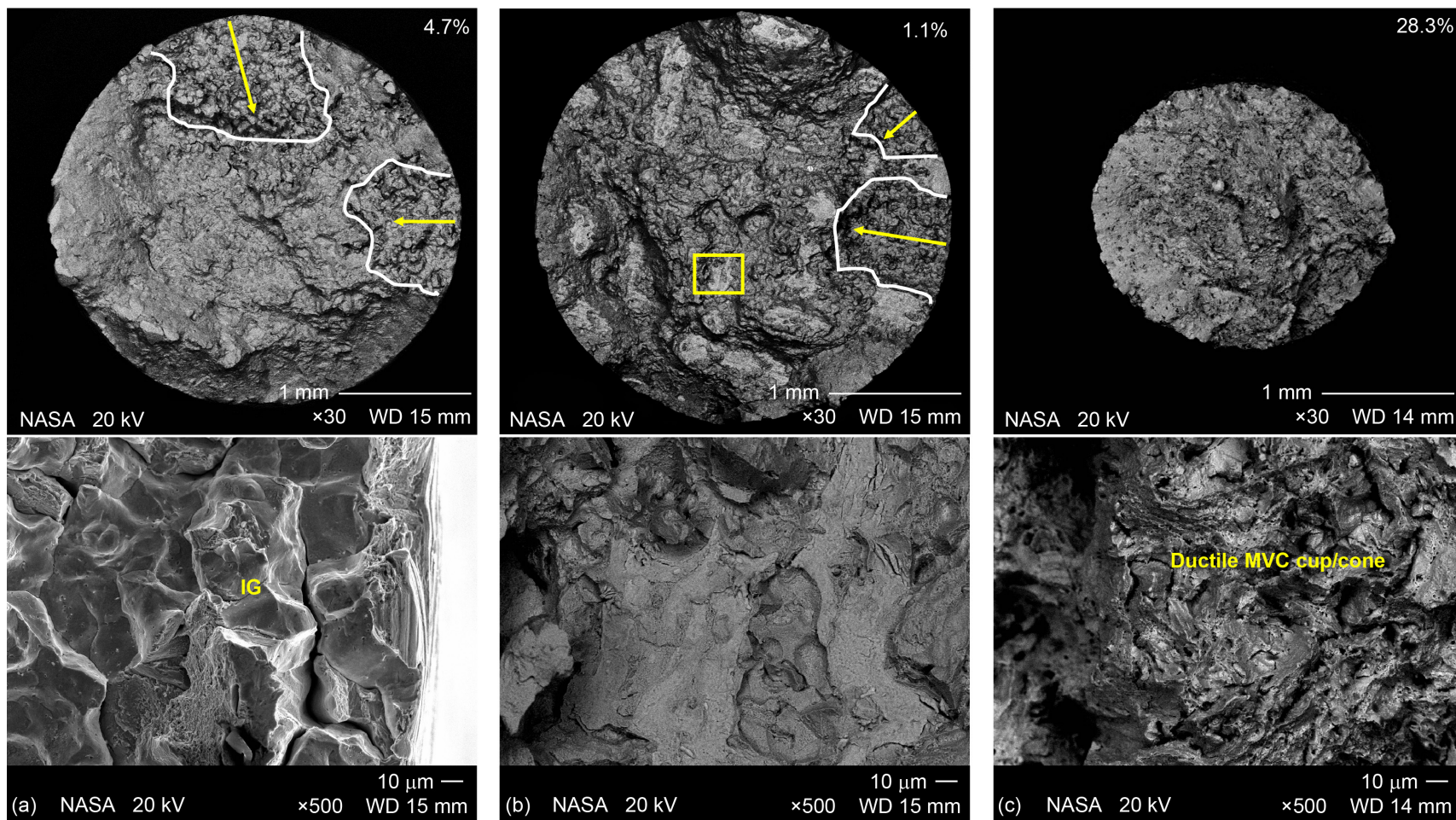


Figure 5. Tensile fractures at 760 °C in build direction, with intergranular (IG) failure regions outlined, Failure strains are indicated at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

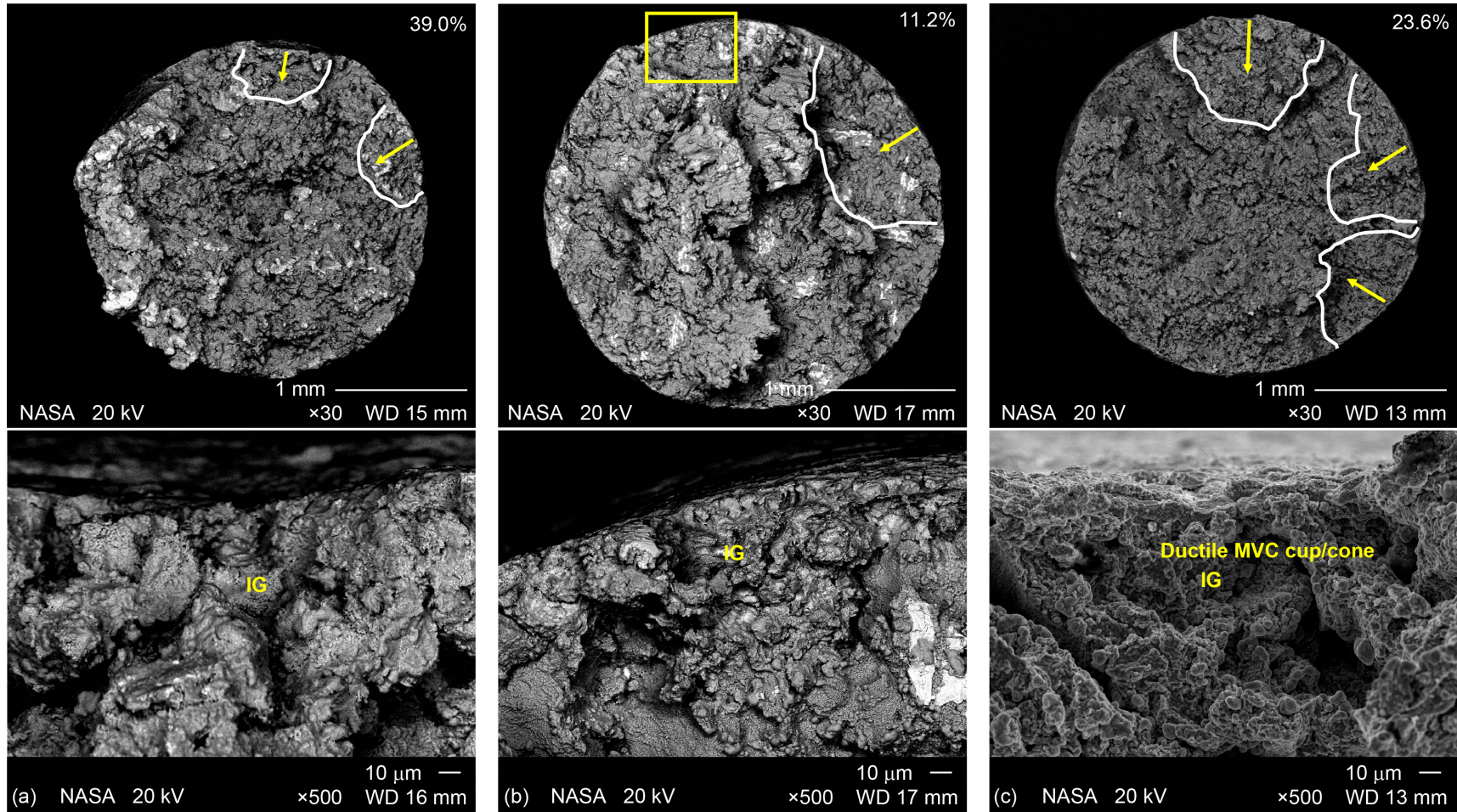


Figure 6. Tensile fractures at 1,093 °C in build direction, with IG failure regions outlined. Failure strains are indicated at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

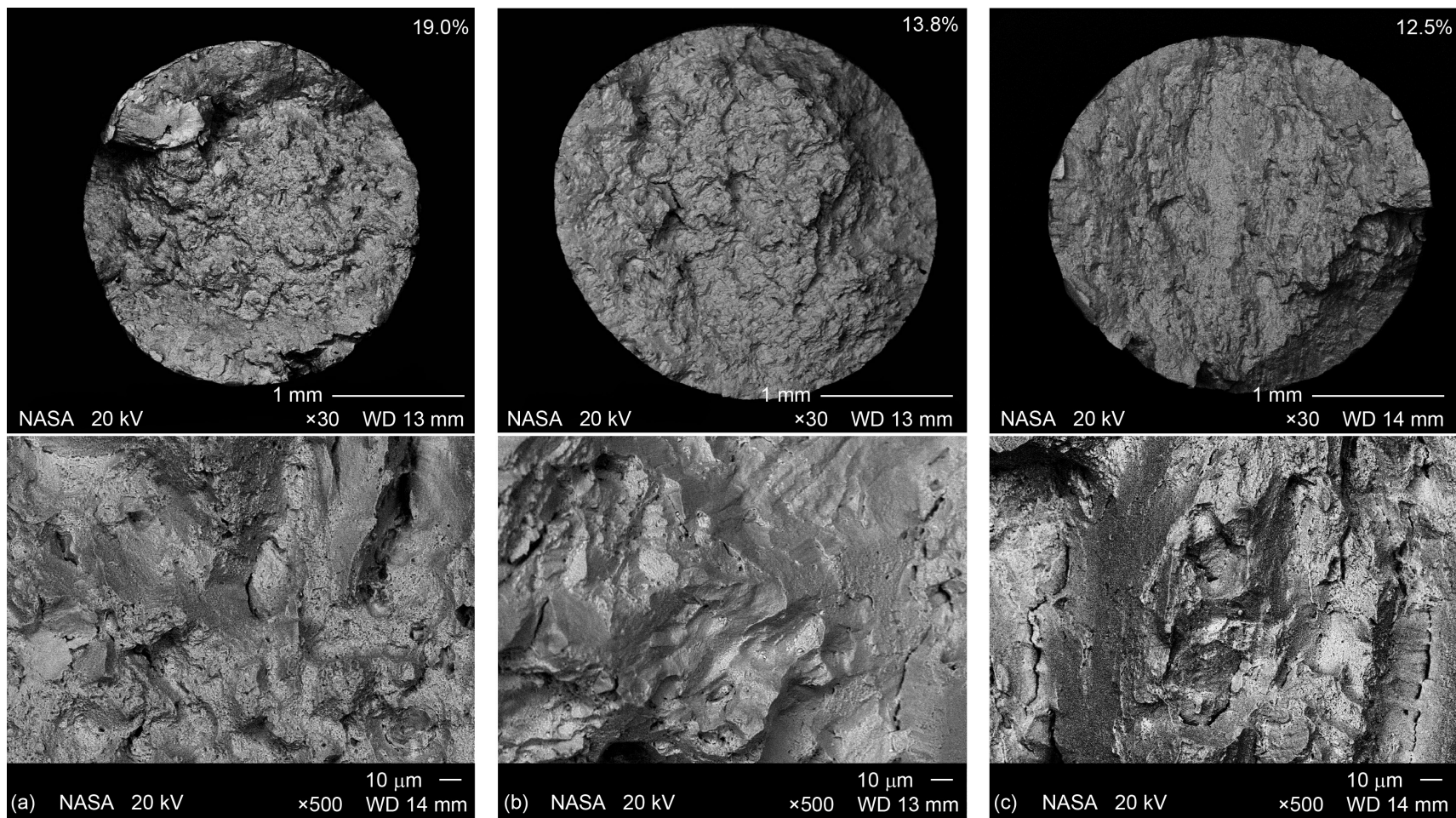


Figure 7. Tensile fractures at 25 °C for specimens oriented transverse to build direction. Failure strains are indicated at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

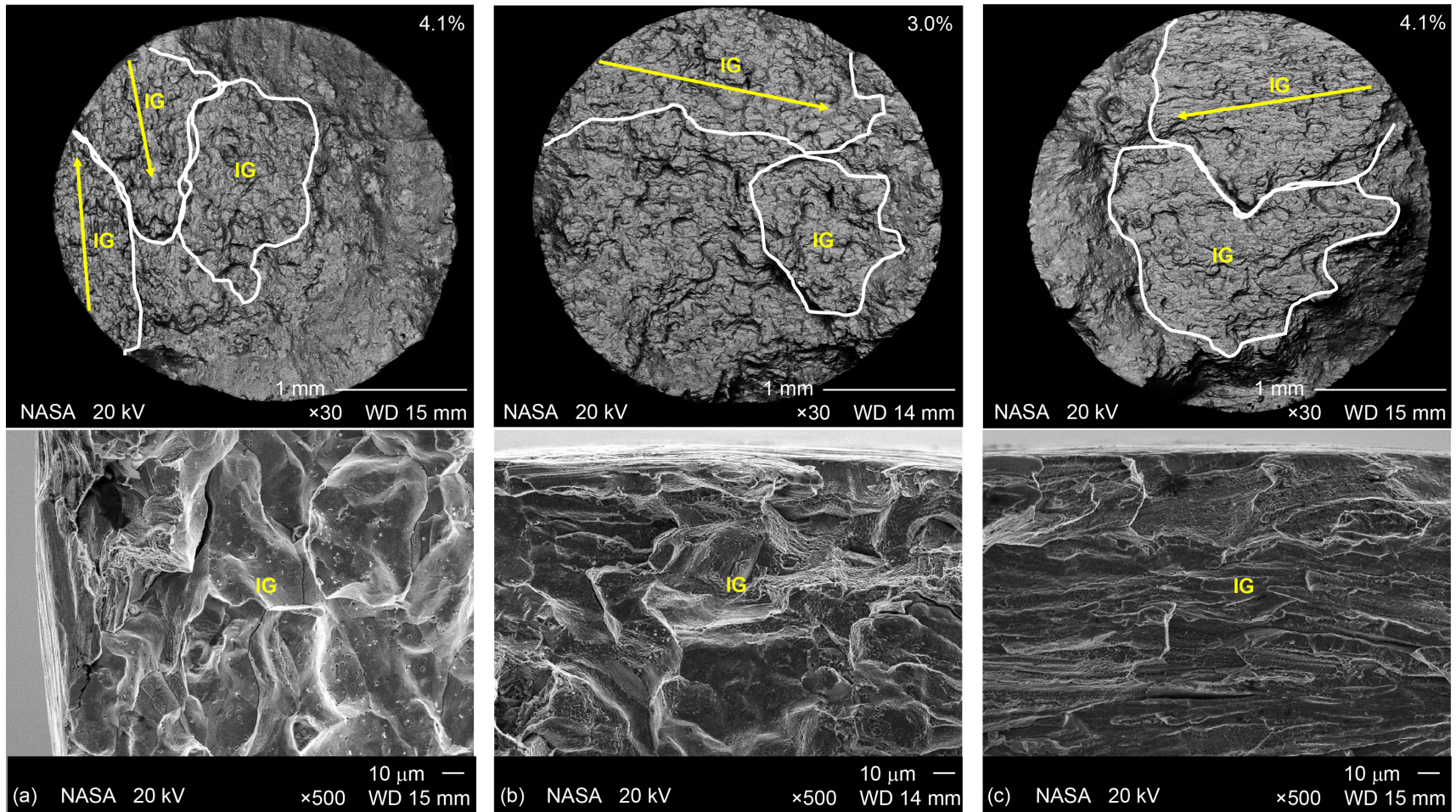


Figure 8. Tensile fractures at 760 °C transverse to build direction, with IG failure regions outlined. Failure strains are indicated at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed

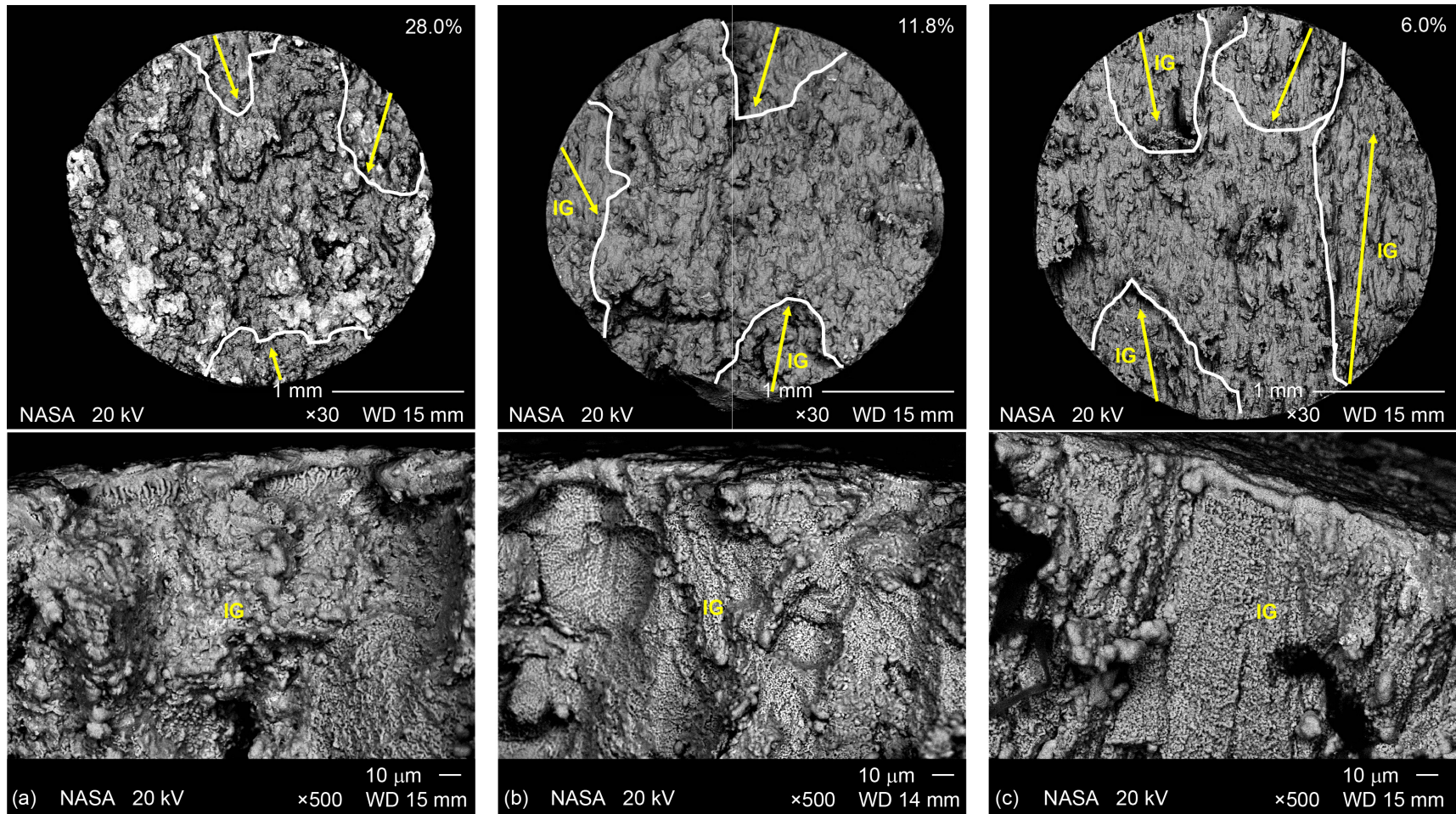


Figure 9. Tensile fractures at 1,093 °C transverse to build direction, with IG failure regions outlined. Failure strains are indicated at top right corner. (a) No-ODS, 28.0% failure strain. (b) Roll-mixed, 11.8% failure strain. (c) Acoustic-mixed, 6.0% failure strain.

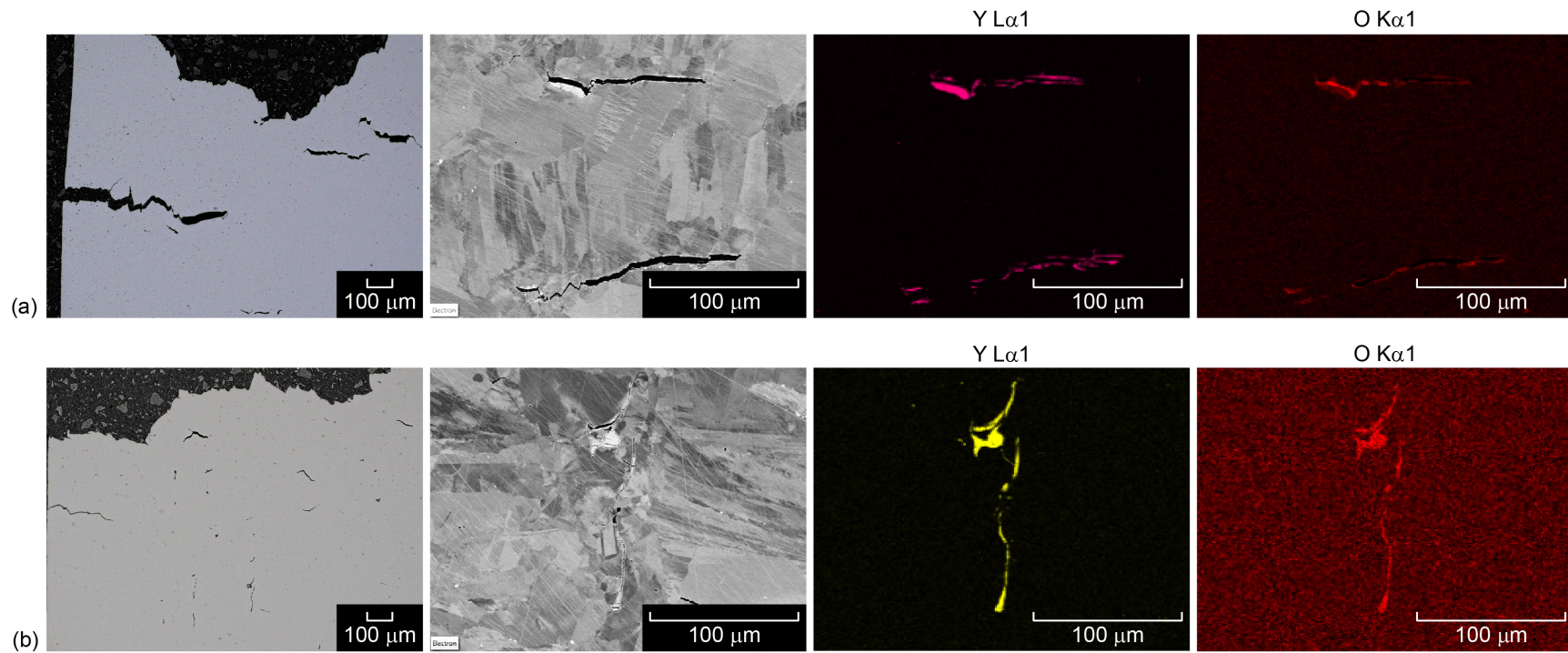


Figure 10. Metallographically polished sections of tensile fractures for roll-mixed specimens tested at 760 °C. Load was applied vertically. (a) In build direction. (b) Transverse to build direction.

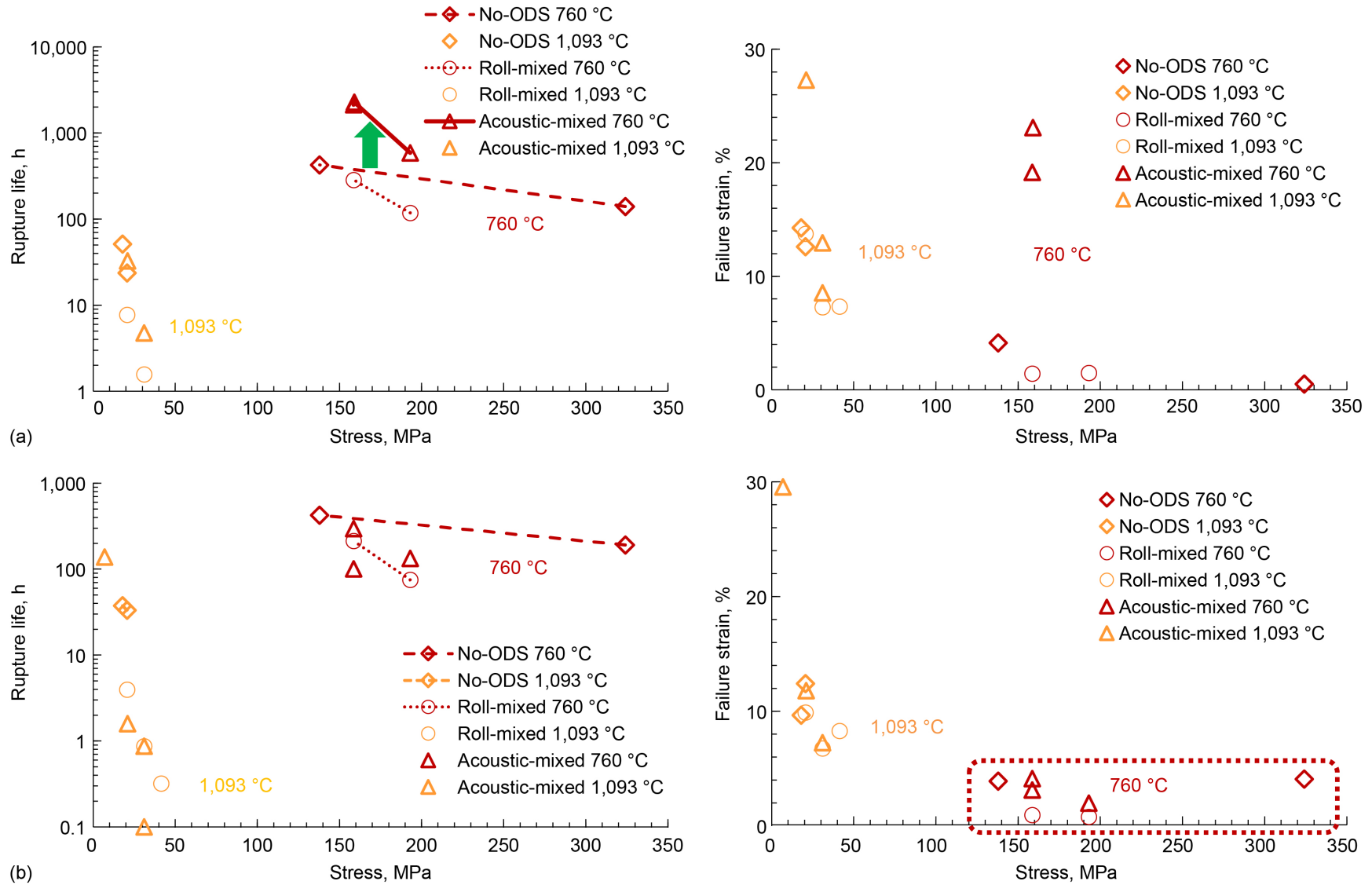


Figure 11. Creep rupture lives and failure strains at different temperatures for specimens. (a) Aligned in build direction. (b) Transverse to build direction.

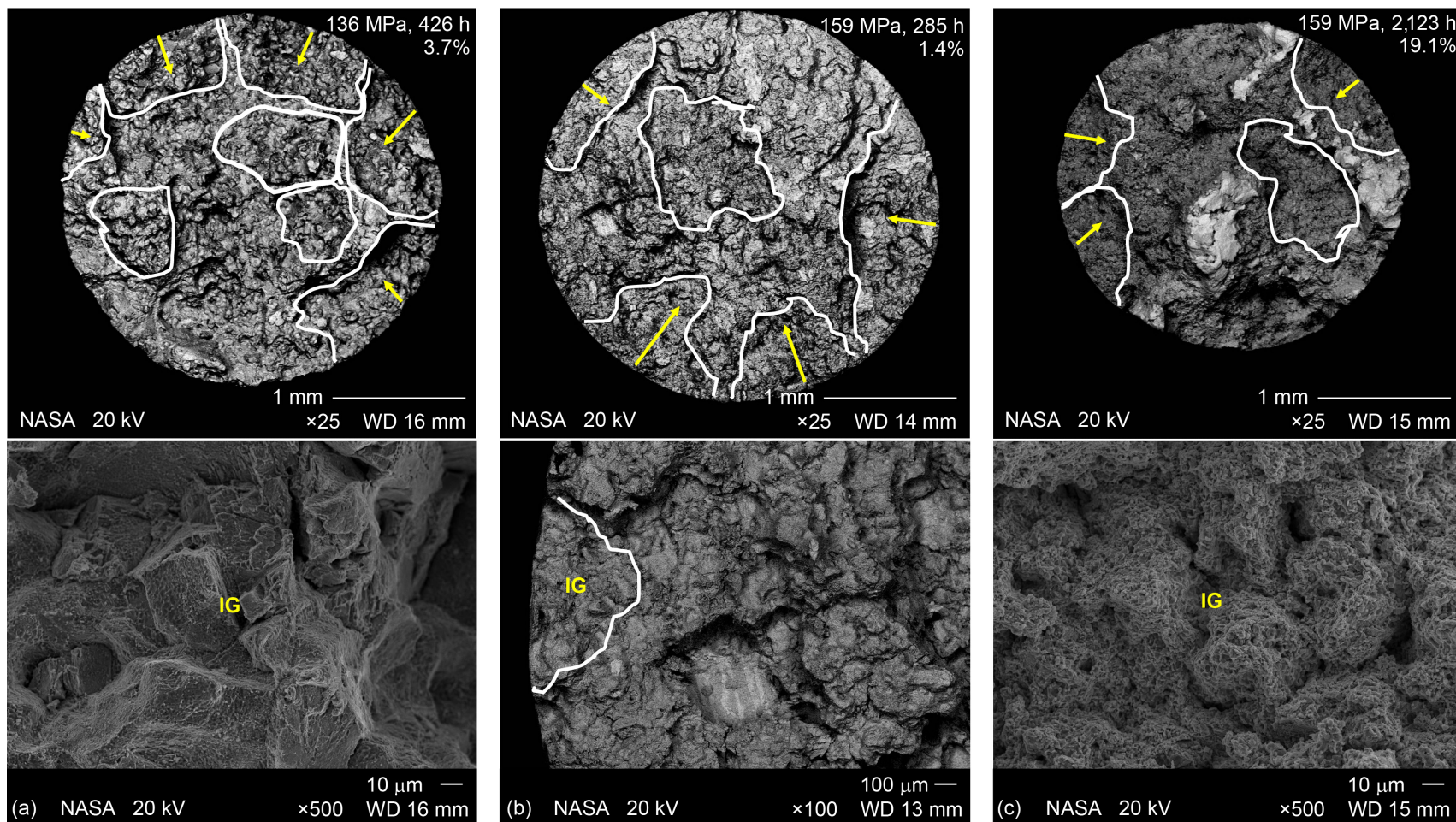


Figure 12. Creep fractures at 760 °C for specimens oriented in build direction, with IG failure regions outlined. Applied stress, rupture life, and failure strain are listed at top right corner. (a) No-ODS. (b) Roll-mixed. and (c) Acoustic-mixed.

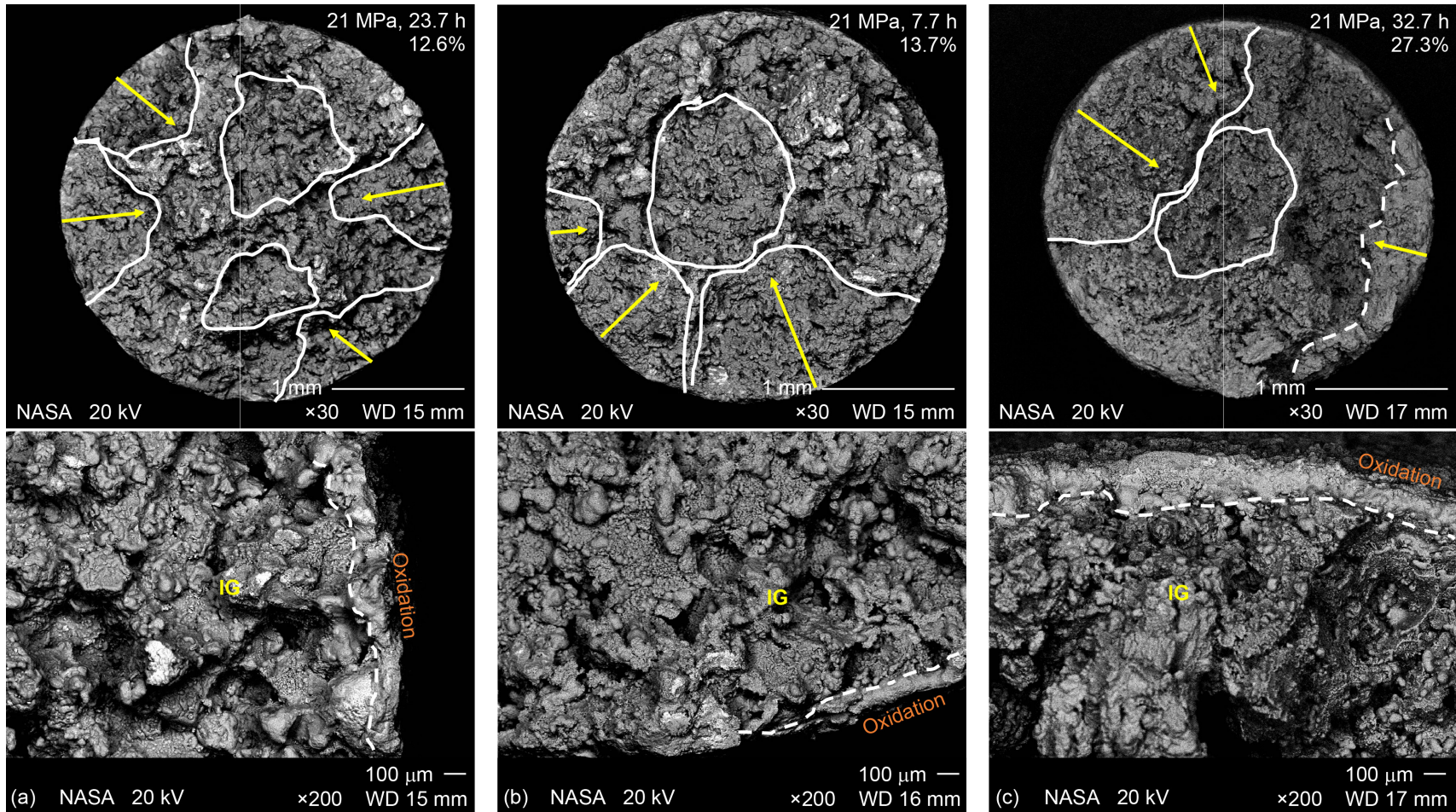


Figure 13. Creep fractures at 1,093 °C in build direction, with IG failure regions outlined. Applied stress, rupture life, and failure strain are listed at top right corner. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

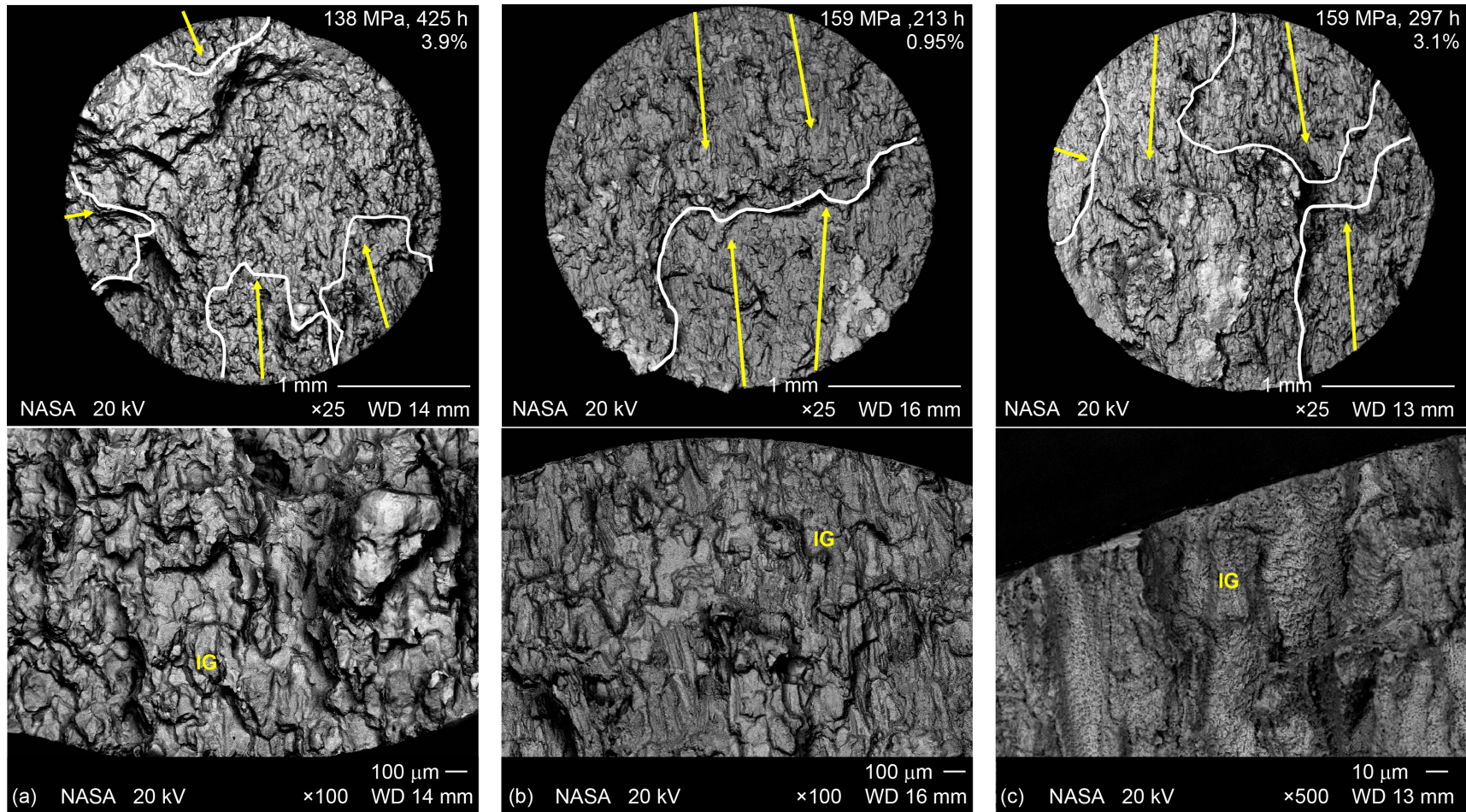


Figure 14. Creep fractures at 760 °C for specimens oriented transverse to build direction, with IG failure regions outlined. Applied stress, rupture life, and failure strain are listed at top right. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

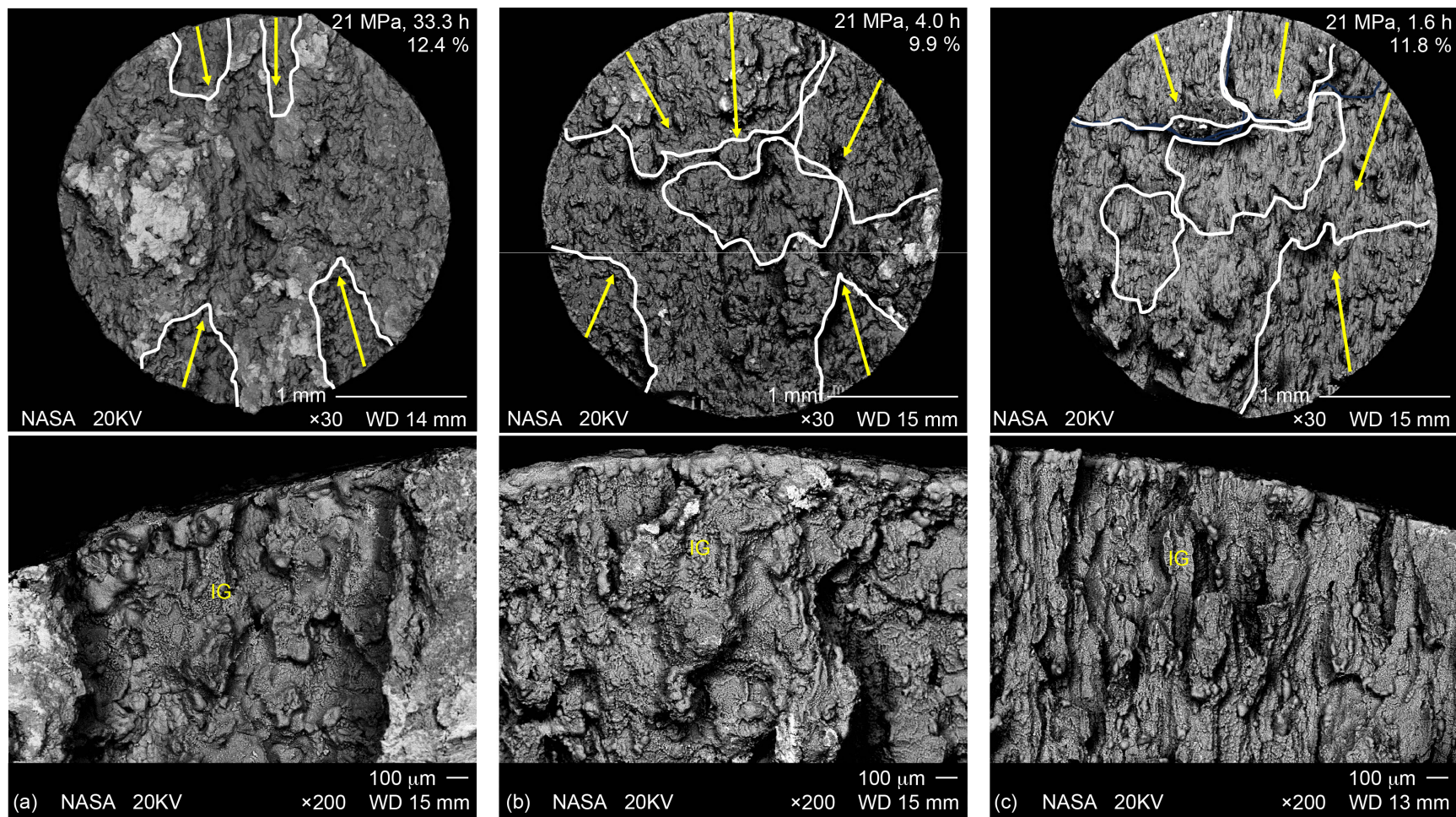


Figure 15. Creep fractures at 1,093 °C transverse to build direction, with IG failure regions outlined. Applied stress, rupture life, and failure strain are listed at top right. (a) No-ODS. (b) Roll-mixed. and (c) Acoustic-mixed.

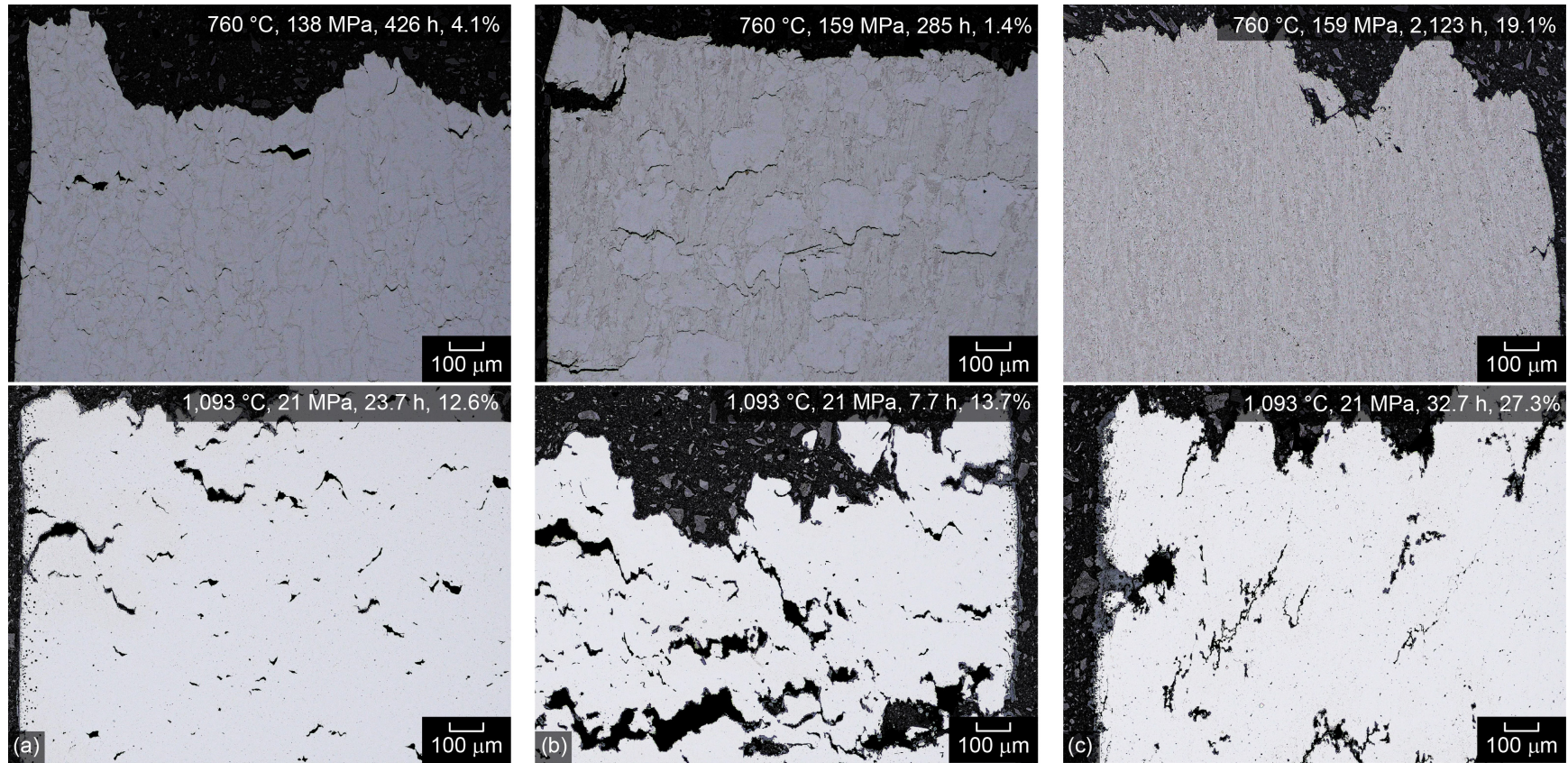


Figure 16. Creep fractures for specimens in build direction, tested at 760 and 1093 °C. Temperature, applied stress, rupture life, and failure strain are listed at top right. (a) No-ODS. (b) Roll-mixed. (c) Acoustic-mixed.

