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Harris et al.

(54) RHENIUM-FREE SINGLE CRYSTAL SUPERALLOY FOR TURBINE BLADES AND VANE APPLICATIONS

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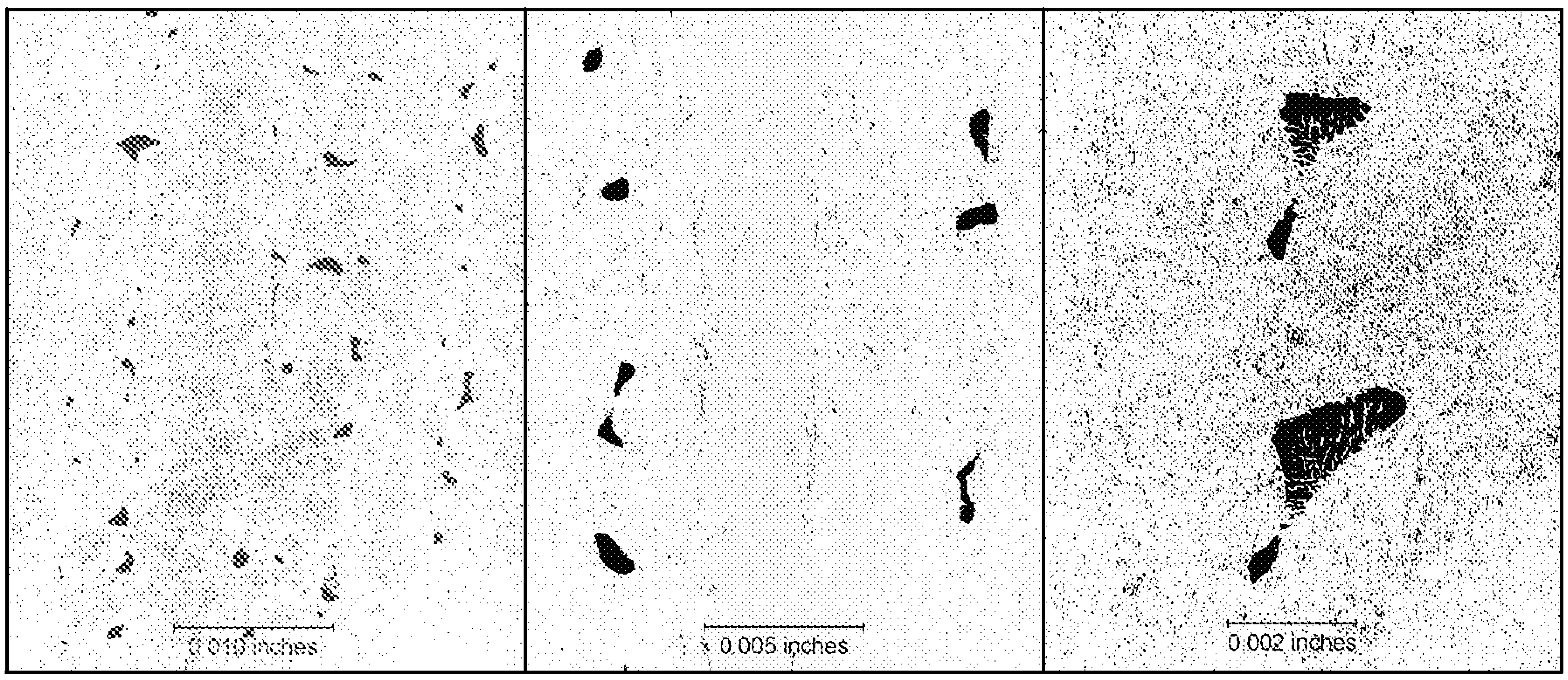
C22C 19/05 (2006.01)

(52) **U.S. Cl.**

USPC .... **416/241 R**; 420/448; 420/443

(57) **ABSTRACT**

A rhenium-free nickel-base superalloy for single crystal casting that exhibits excellent high temperature creep resistance, while also exhibiting other desirable properties for such alloys, comprises 5.60% to 5.85% aluminum, 9.4% to 9.9% cobalt, 5.0% to 6.0% chromium, 0.08% 0.35% hafnium, 0.50% to 0.70% molybdenum, 8.0% to 9.0% tantalum, 0.60% to 0.90% titanium, 8.5% to 9.8% tungsten, the balance comprising nickel and minor amounts of incidental elements.



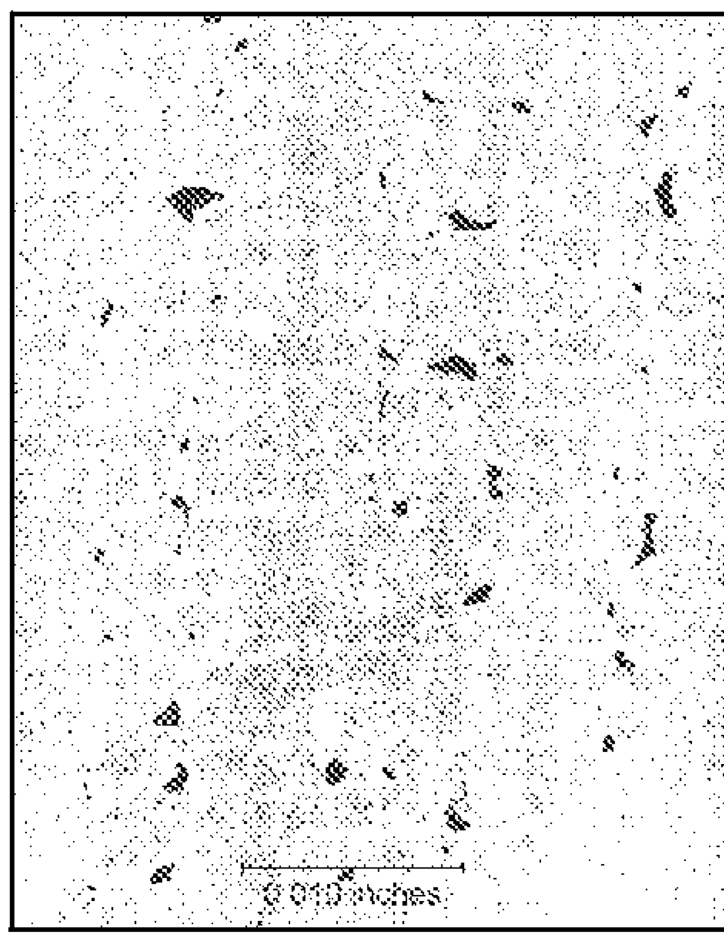


FIG. 1A

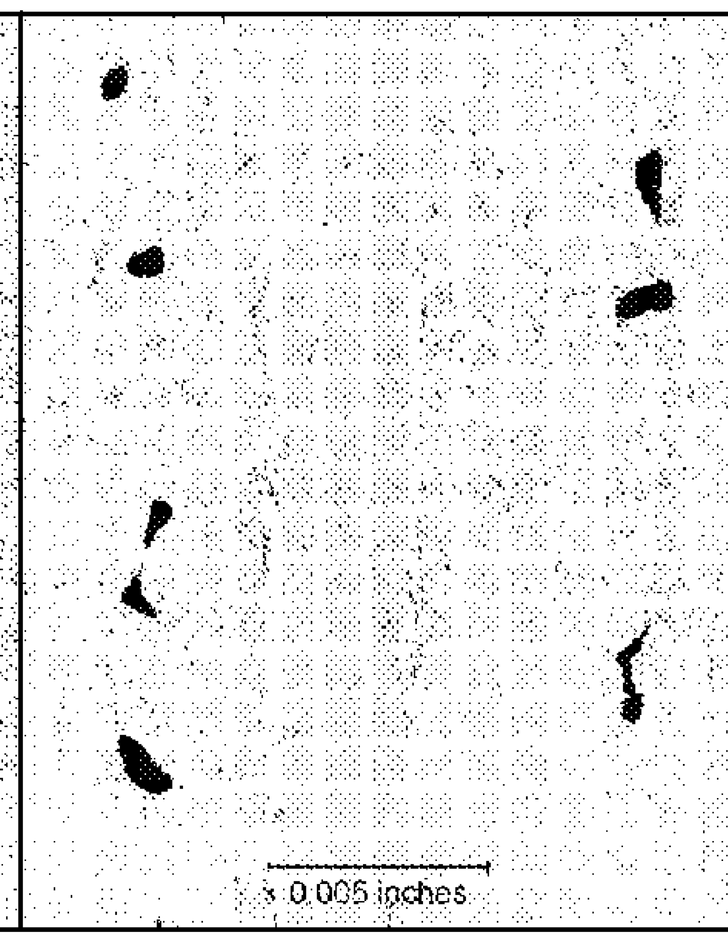


FIG. 1B

FIG. 1C

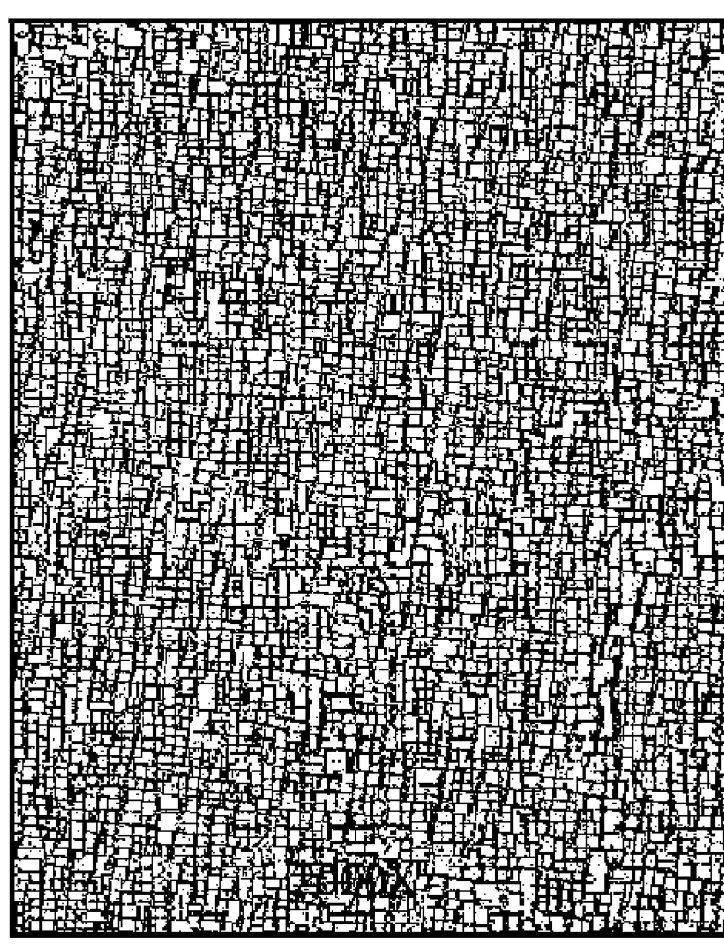


FIG. 2A

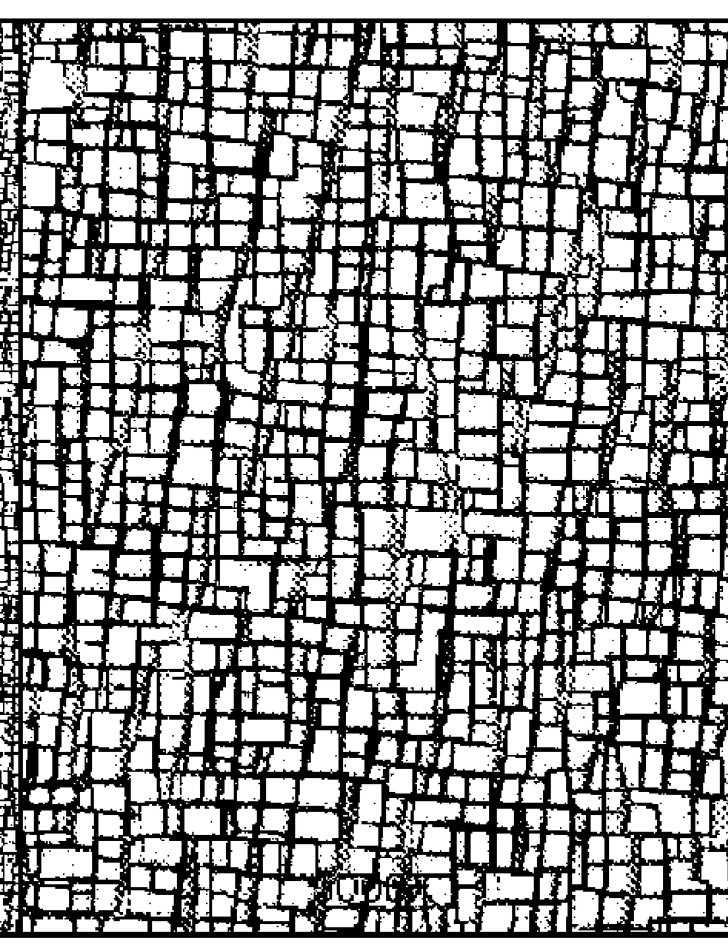


FIG. 2B

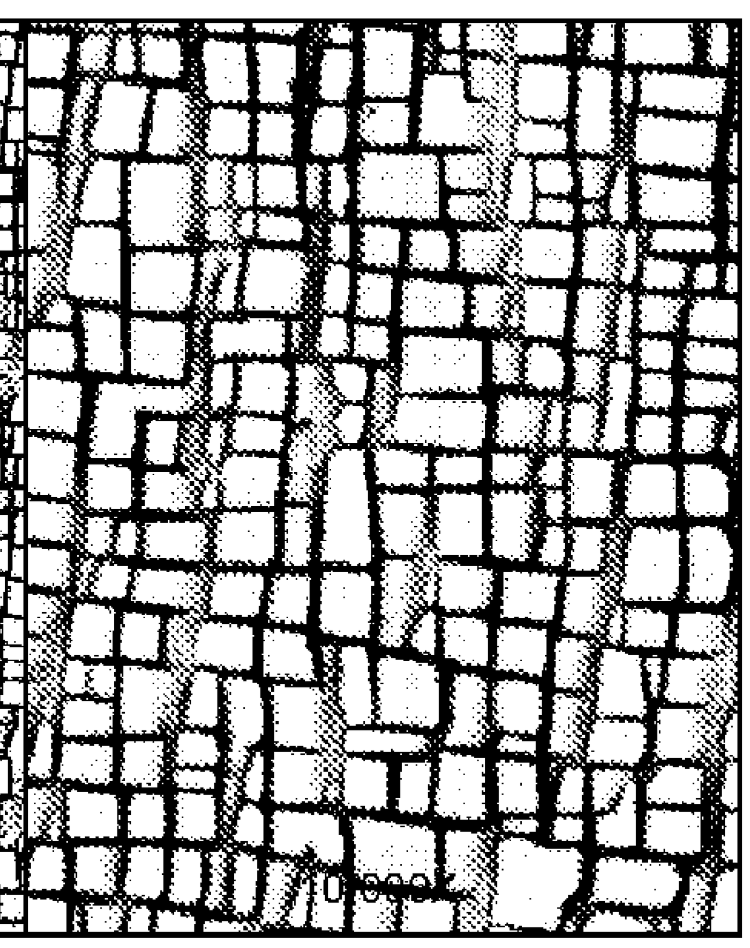


FIG. 2C

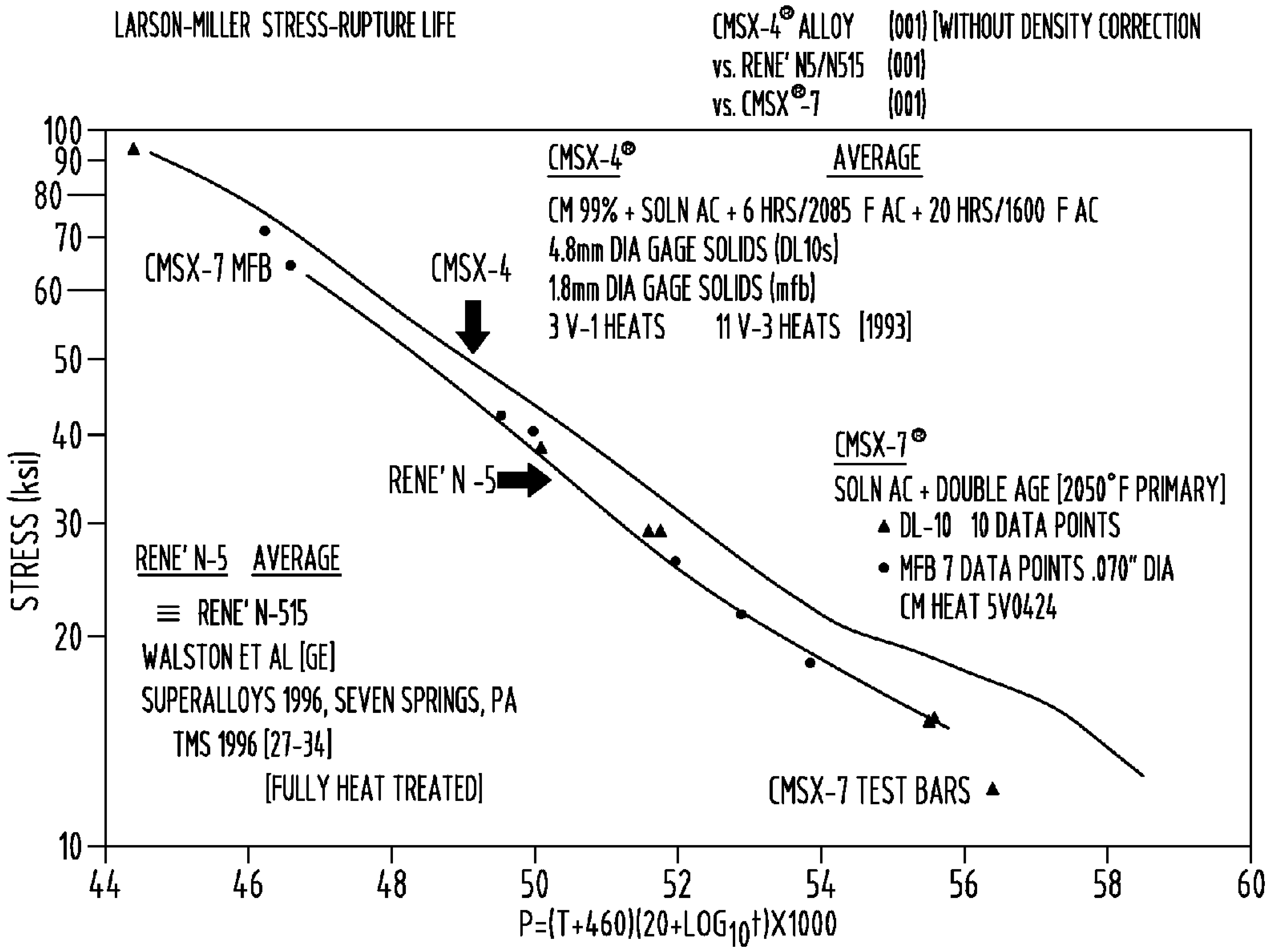

LARSON-MILLER STRESS-RUPTURE LIFE
CMSX-4® ALLOY (001) [WITHOUT DENSITY CORRECTION
vs. RENE' N5/N515 (001)
vs. CMSX®-7 (001)
CMSX-4® AVERAGE
CM 99% + SOLN AC + 6 HRS/2085 F AC + 20 HRS/1600 F AC
4.8mm DIA GAGE SOLIDS (DL10s)
1.8mm DIA GAGE SOLIDS (mfb)
3 V-1 HEATS 11 V-3 HEATS [1993]
CMSX-7 MFB
CMSX-4
RENE' N -5
CMSX-7®
SOLN AC + DOUBLE AGE [2050°F PRIMARY]
DL-10 10 DATA POINTS
MFB 7 DATA POINTS .070" DIA
CM HEAT 5V0424
RENE' N-5 AVERAGE
≡ RENE' N-515
WALSTON ET AL [GE]
SUPERALLOYS 1996, SEVEN SPRINGS, PA
TMS 1996 [27-34]
[FULLY HEAT TREATED]
CMSX-7 TEST BARS
STRESS (ksi)
P=(T+460)(20+LOG10t)X1000

FIG. 3

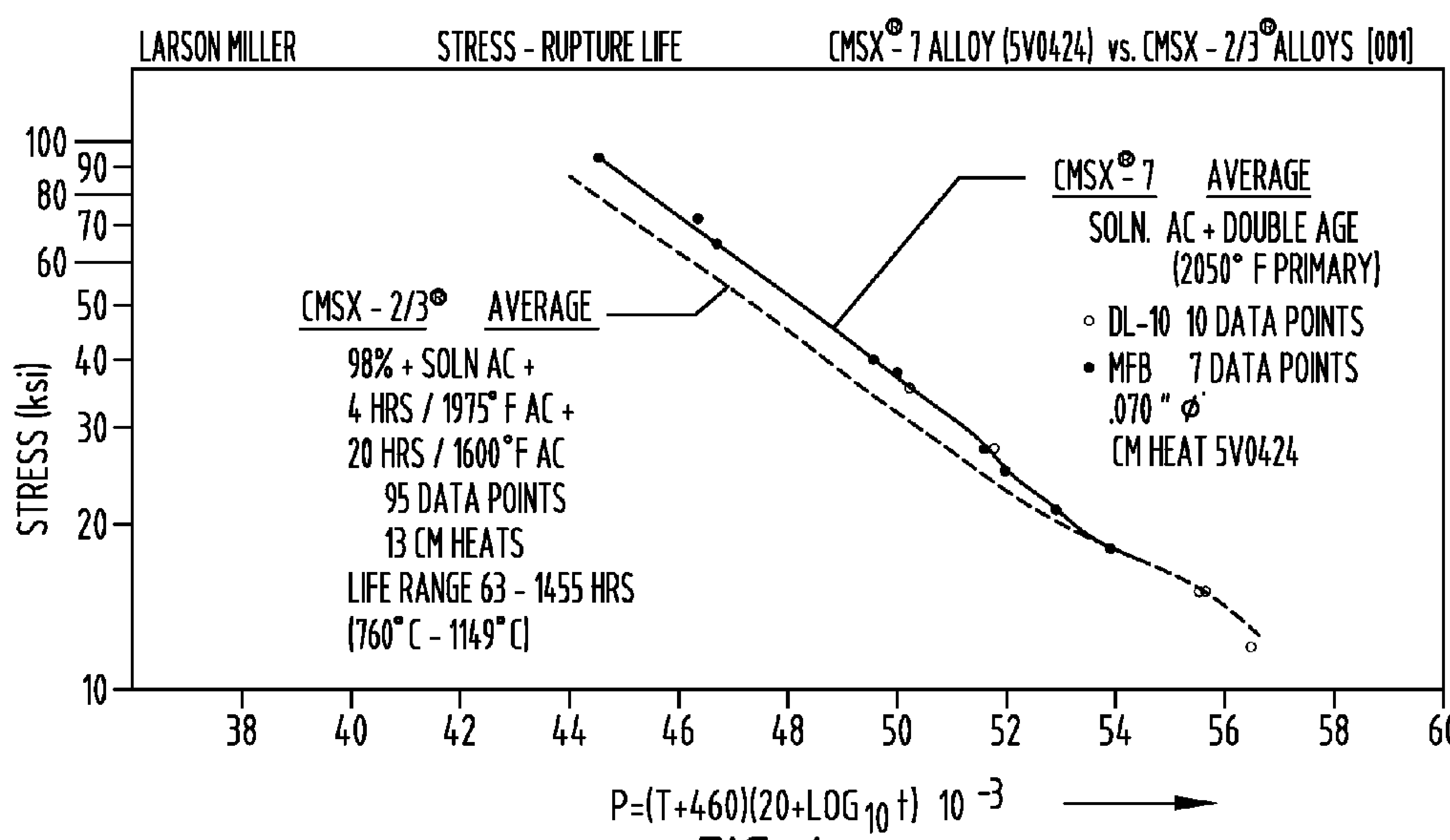

LARSON MILLER
STRESS - RUPTURE LIFE
CMSX®- 7 ALLOY (5V0424) vs. CMSX - 2/3® ALLOYS [001]
CMSX® - 7 AVERAGE
SOLN. AC + DOUBLE AGE
(2050° F PRIMARY)
DL-10 10 DATA POINTS
MFB 7 DATA POINTS
.070 " ϕ
CM HEAT 5V0424
CMSX - 2/3® AVERAGE
98% + SOLN AC +
4 HRS / 1975° F AC +
20 HRS / 1600°F AC
95 DATA POINTS
13 CM HEATS
LIFE RANGE 63 - 1455 HRS
(760° C - 1149° C)
STRESS (ksi)
P=(T+460)(20+LOG10 t) 10 -3

FIG. 4

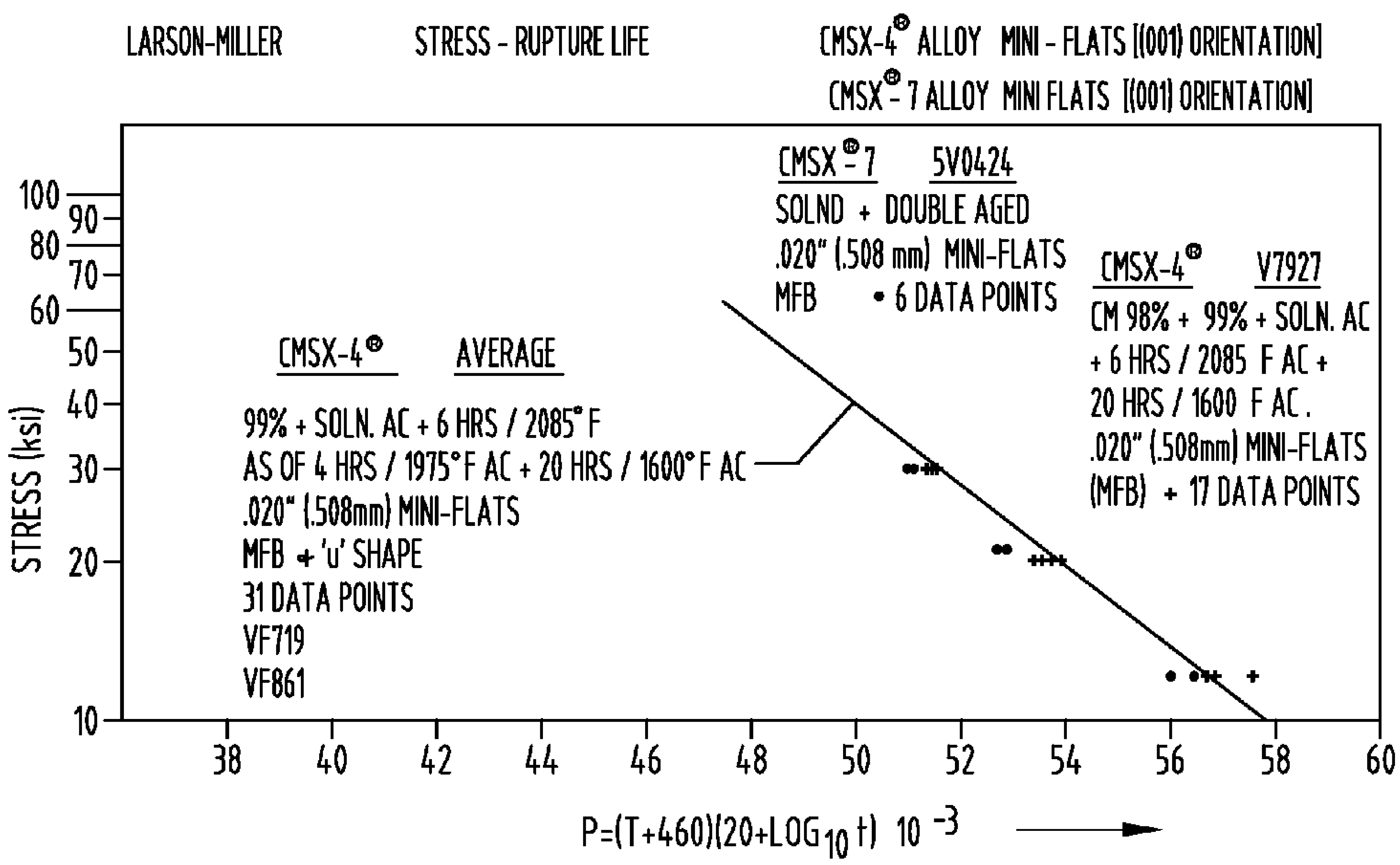


FIG. 5

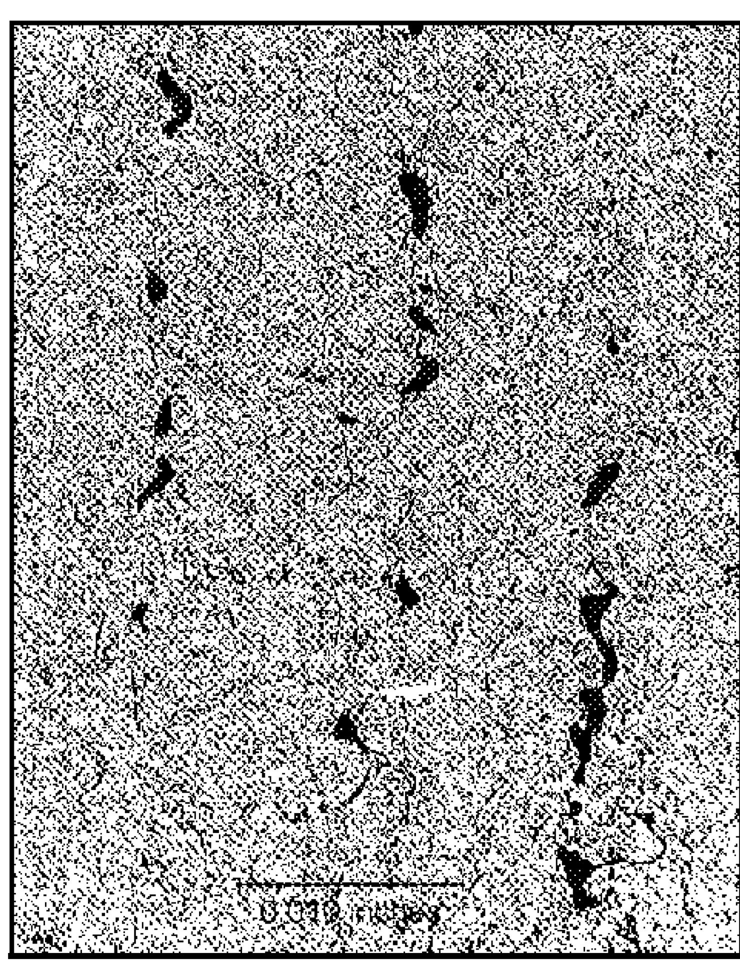


FIG. 6A

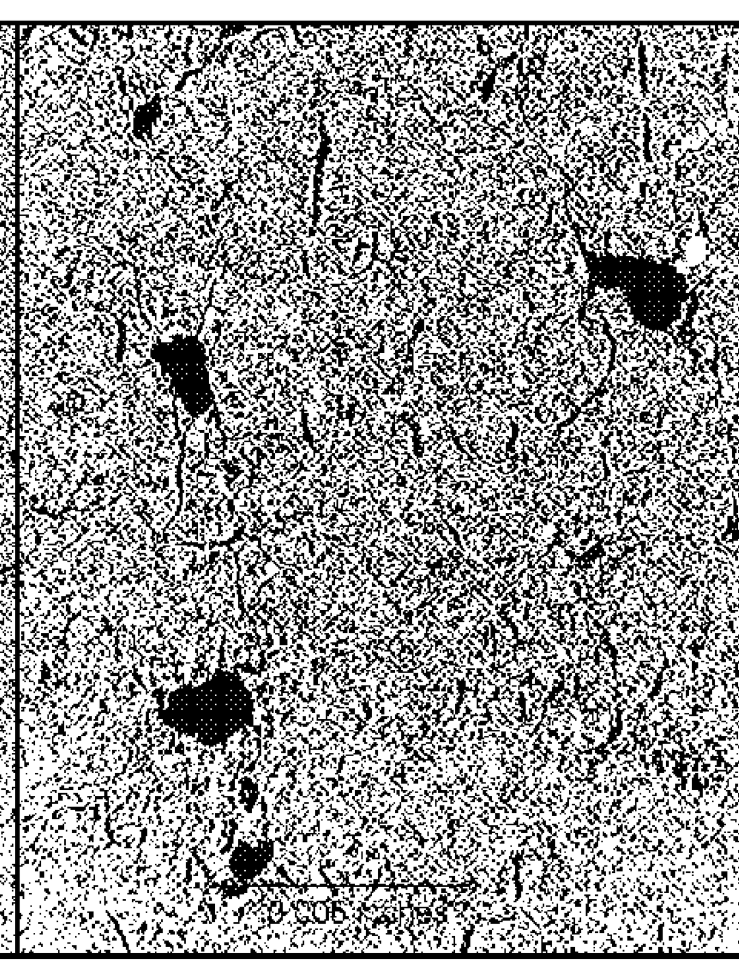


FIG. 6B

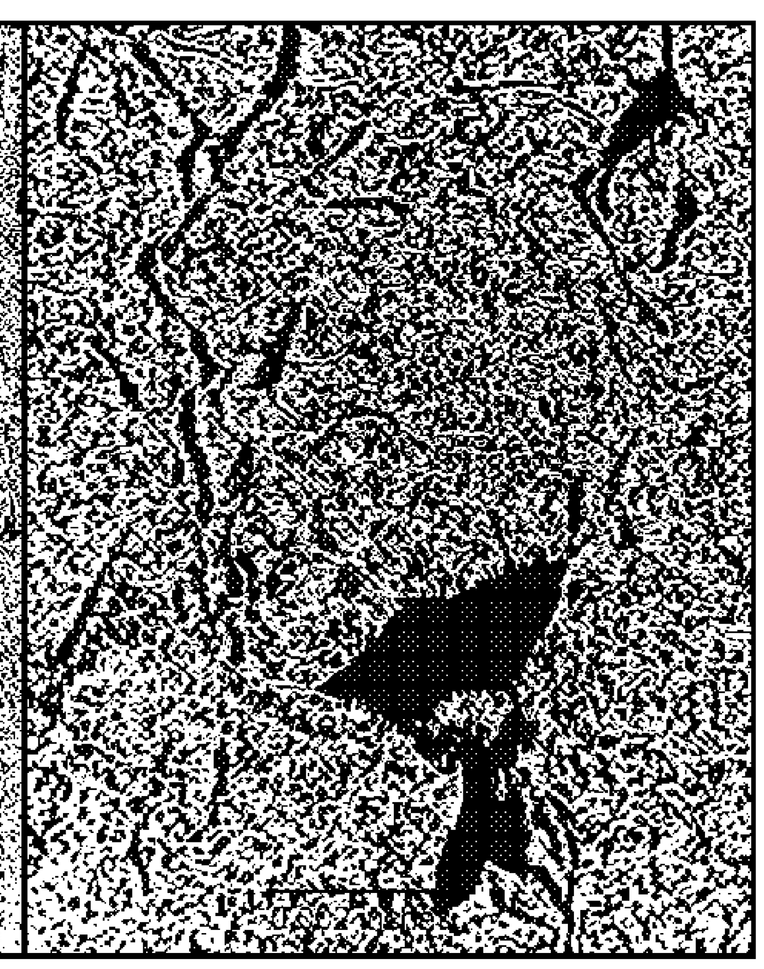


FIG. 6C

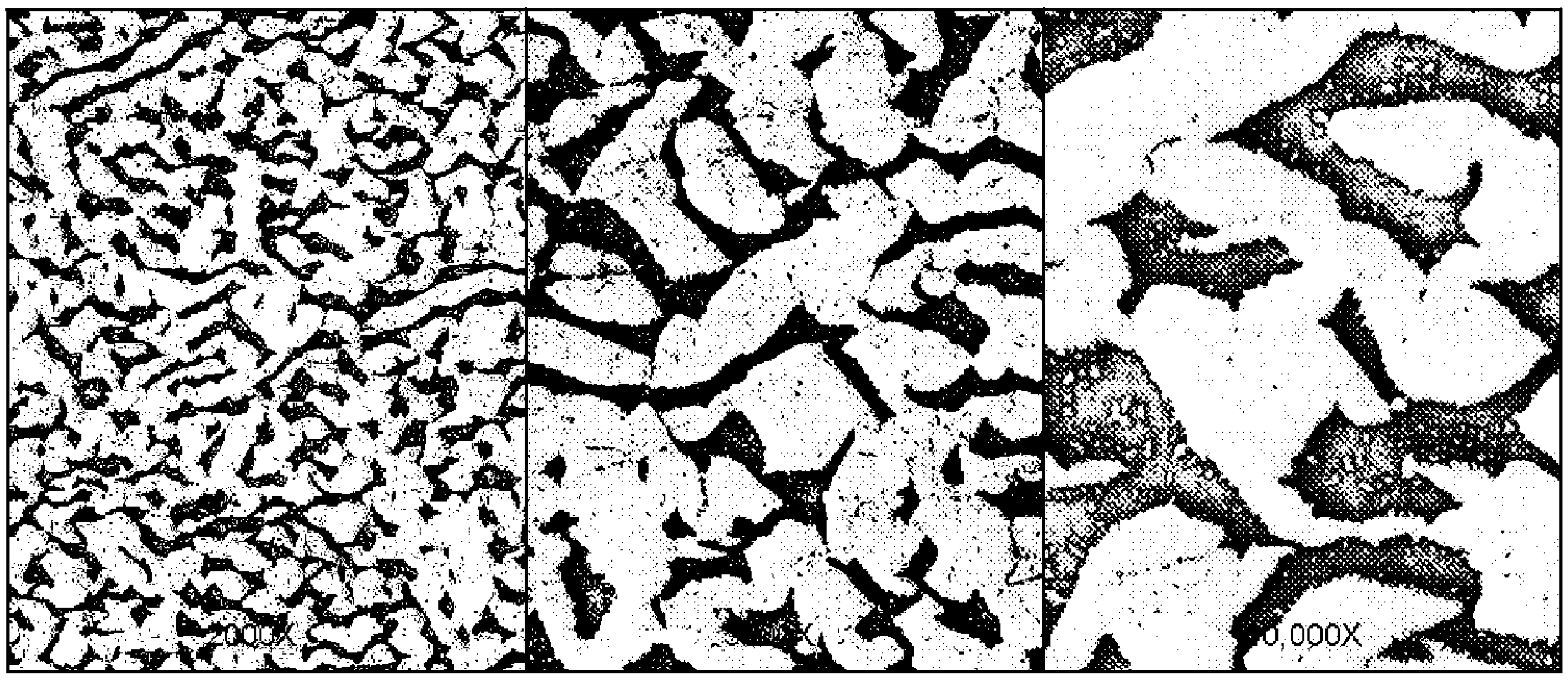


FIG. 7A FIG. 7B FIG. 7C

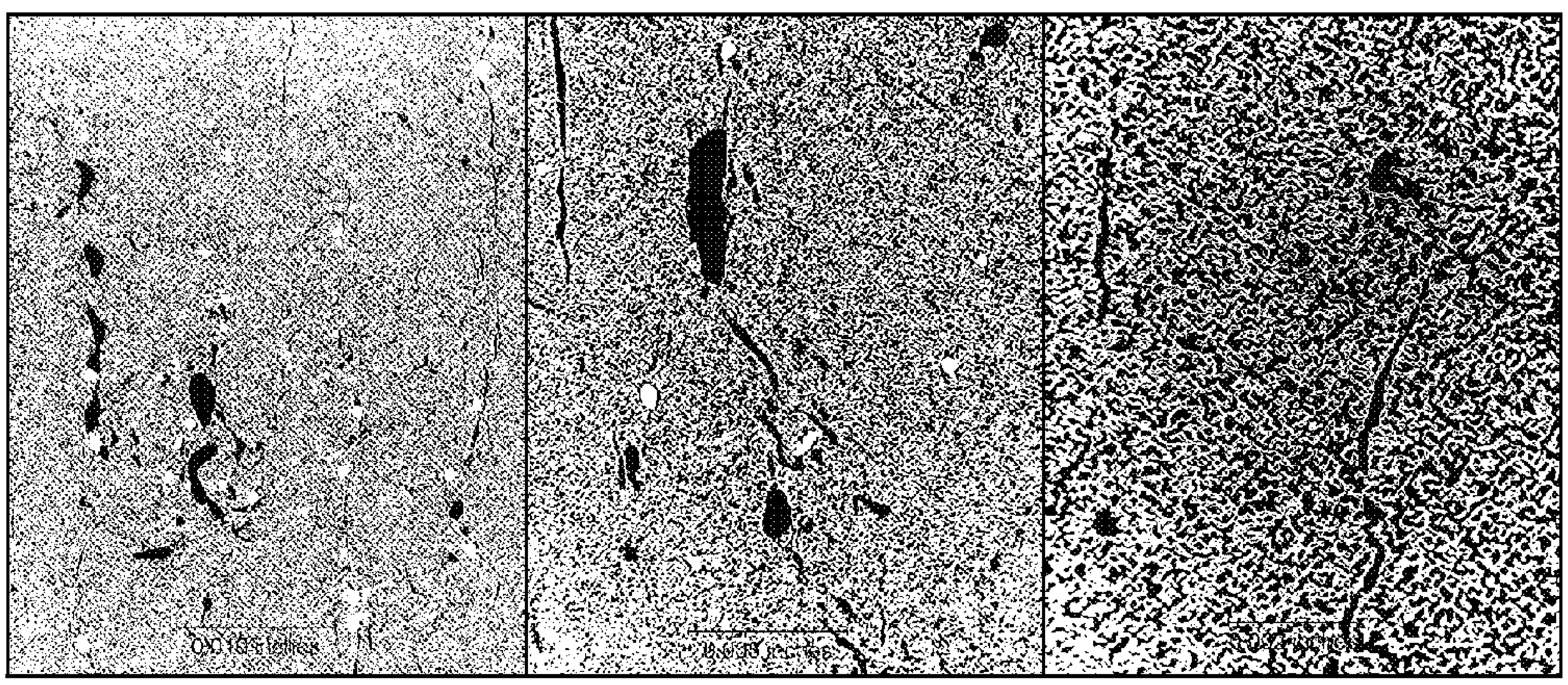


FIG. 8A FIG. 8B FIG. 8C

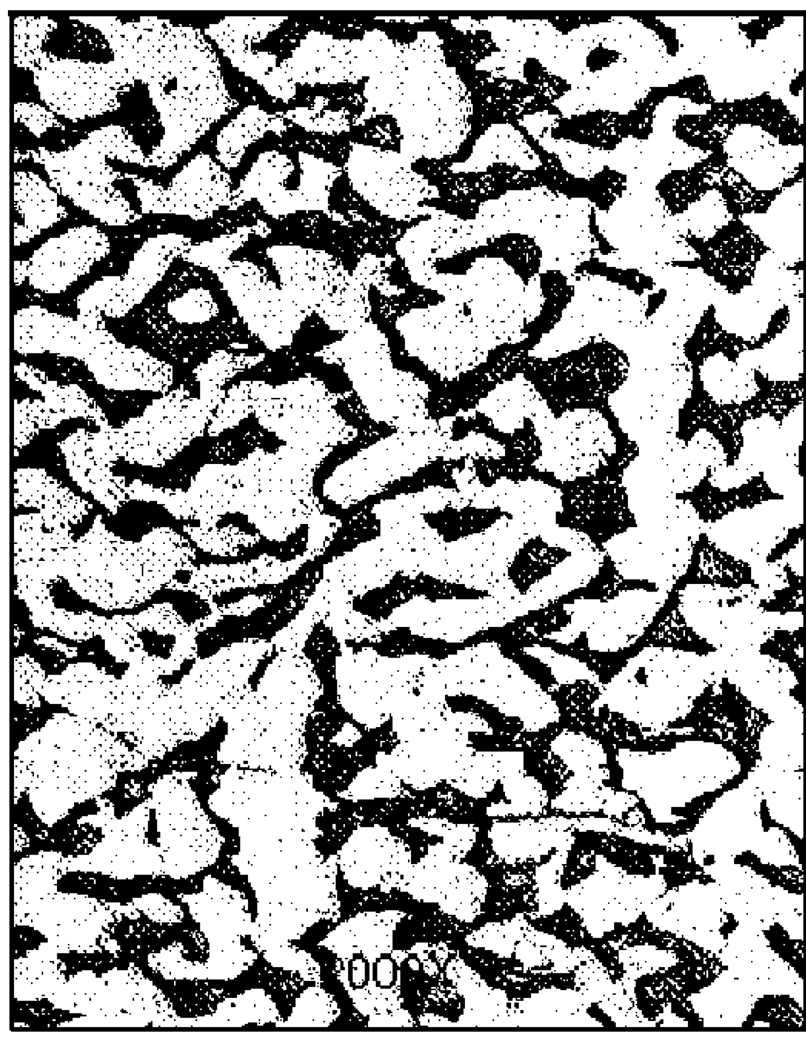


FIG. 9A

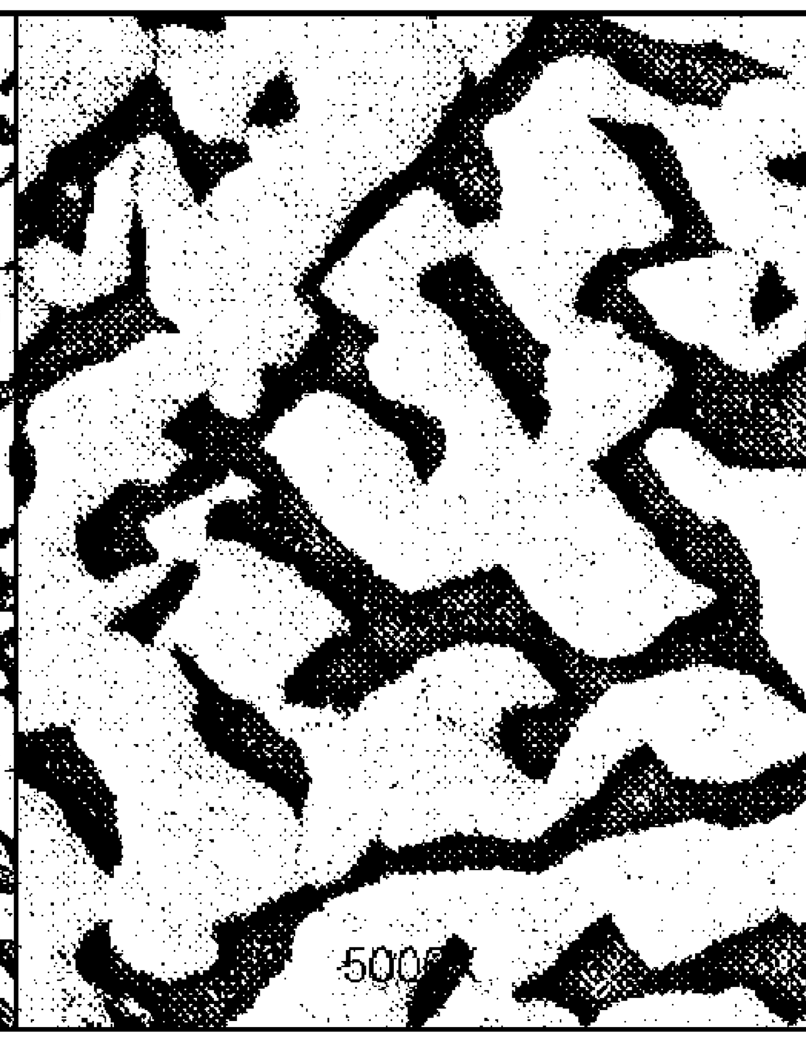


FIG. 9B

FIG. 9C

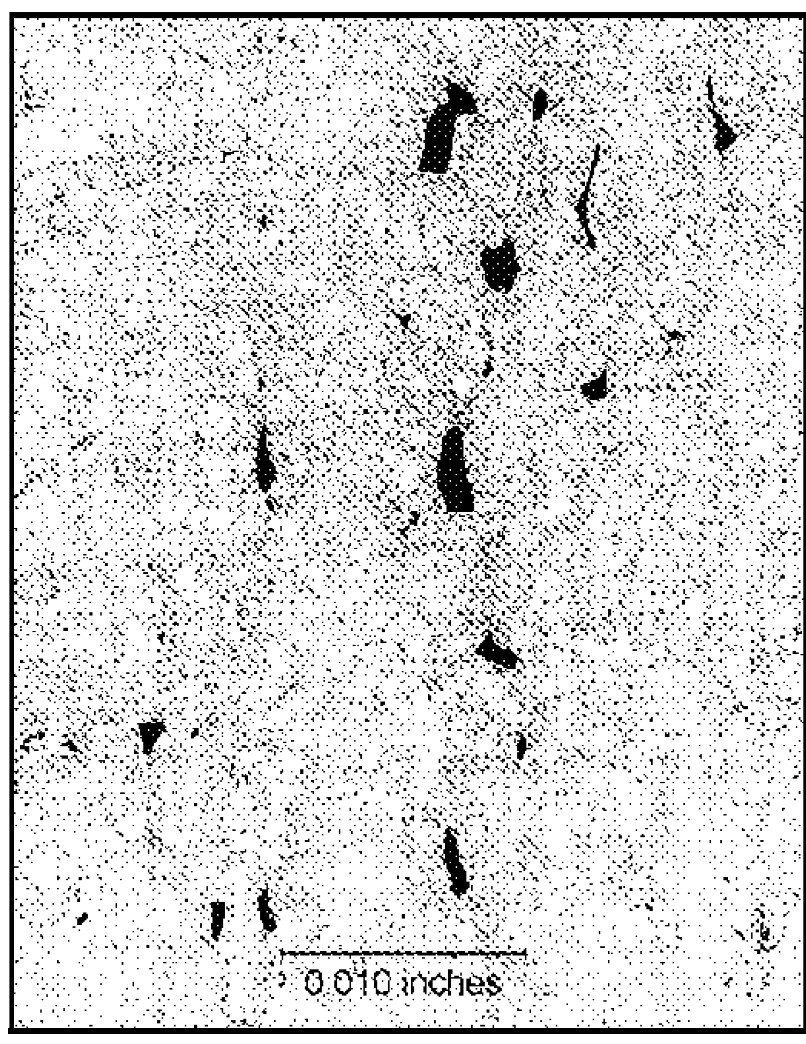


FIG. 10A

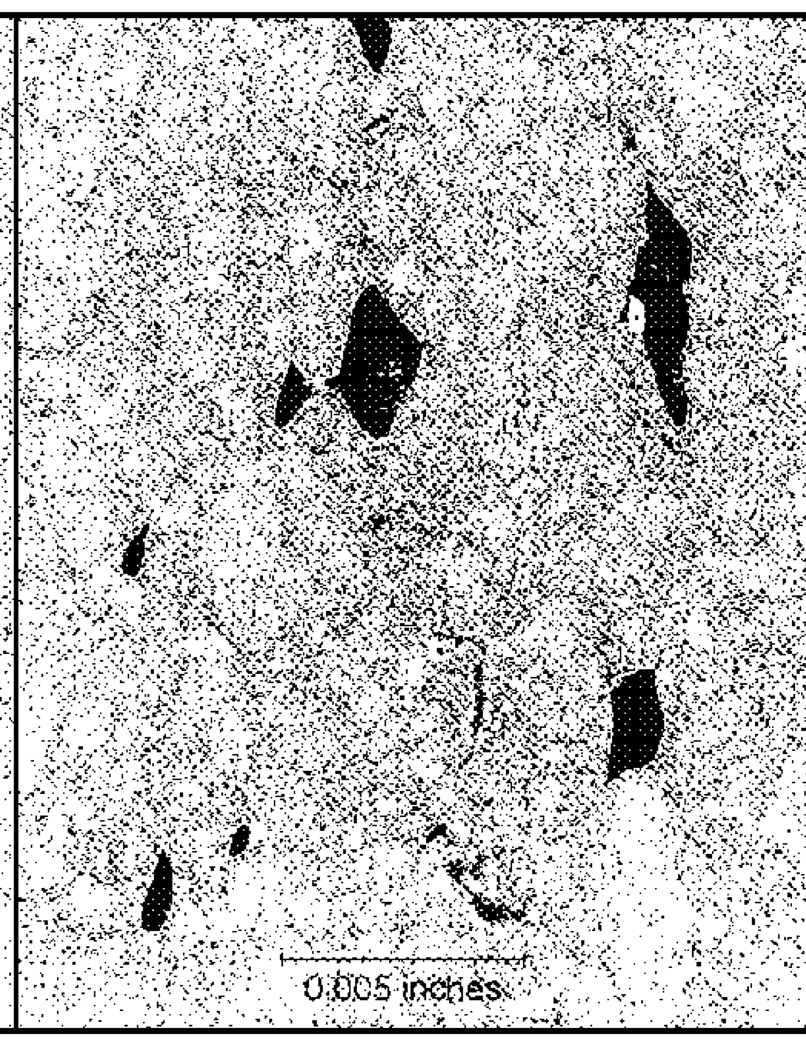


FIG. 10B

FIG. 10C

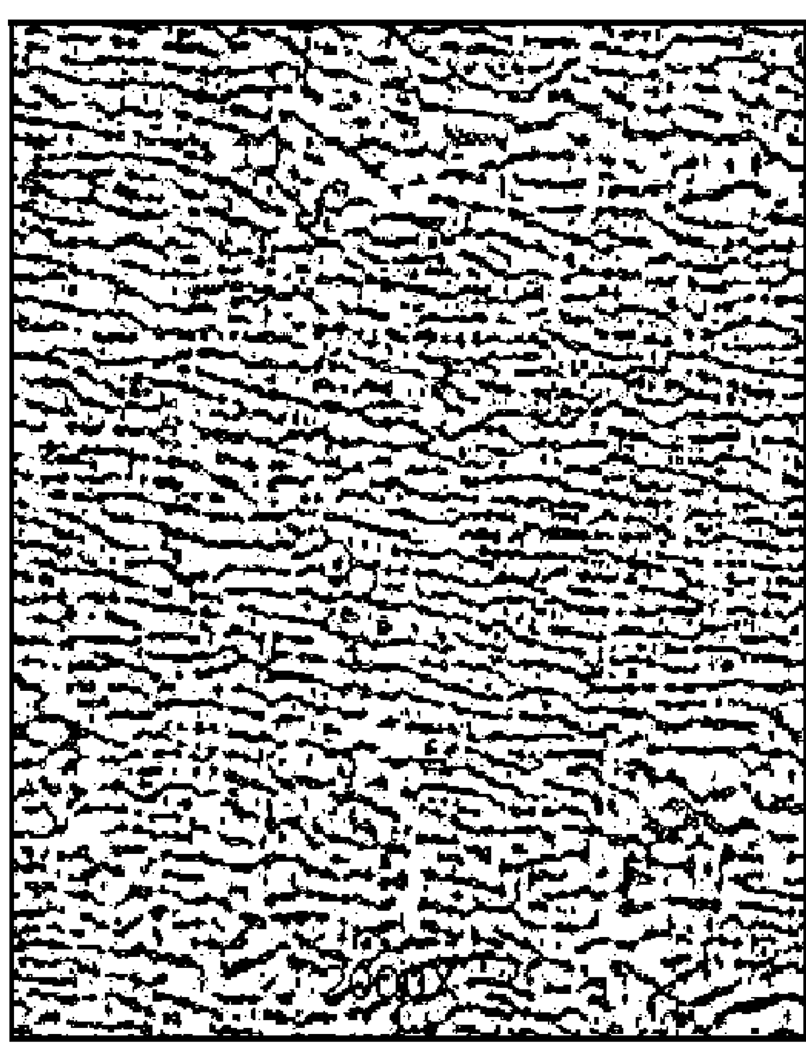


FIG. 11A

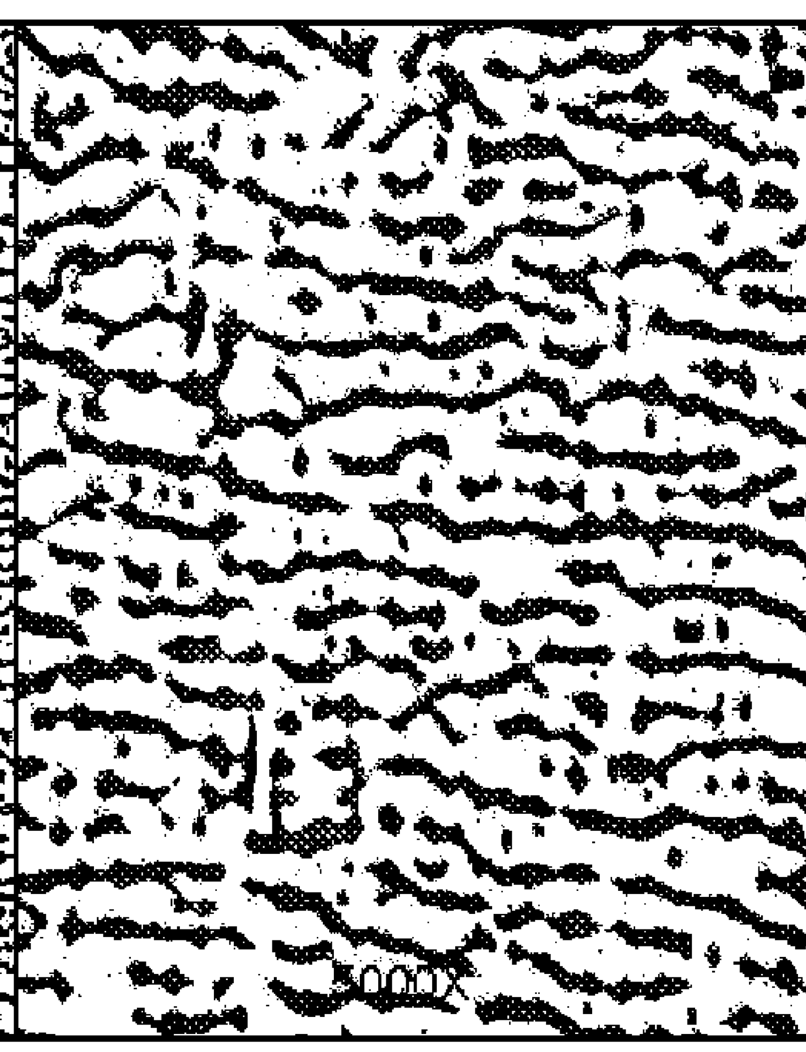


FIG. 11B

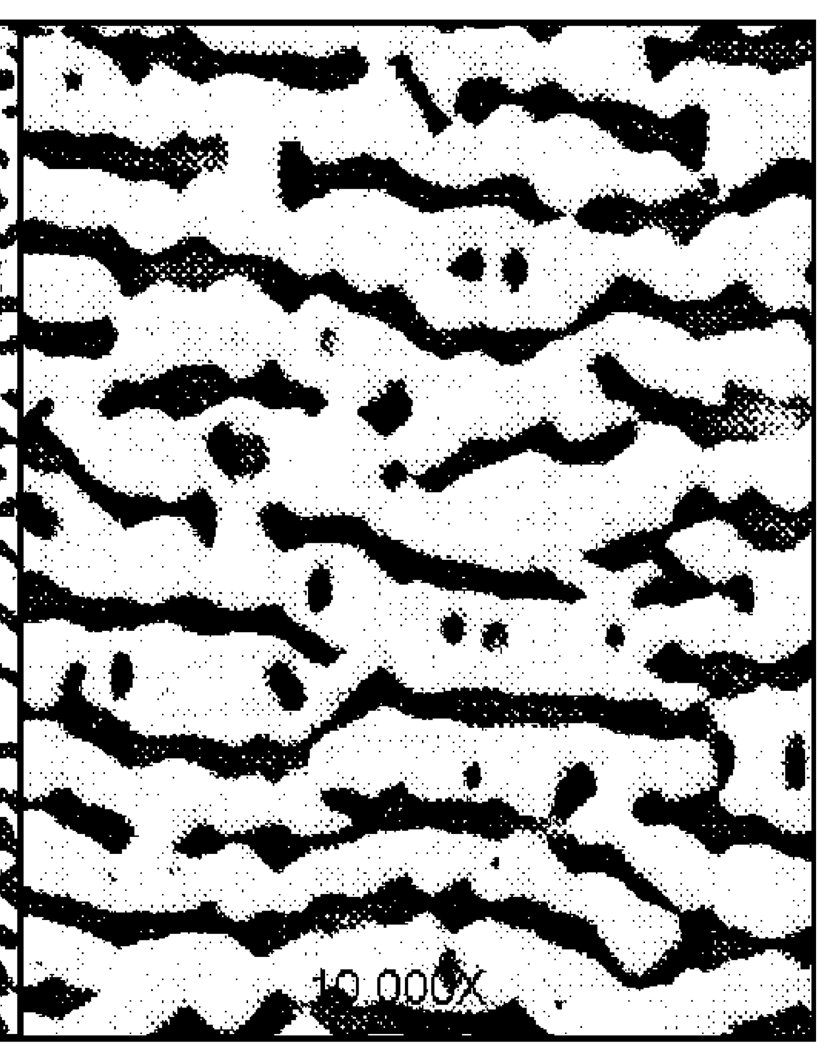


FIG. 11C

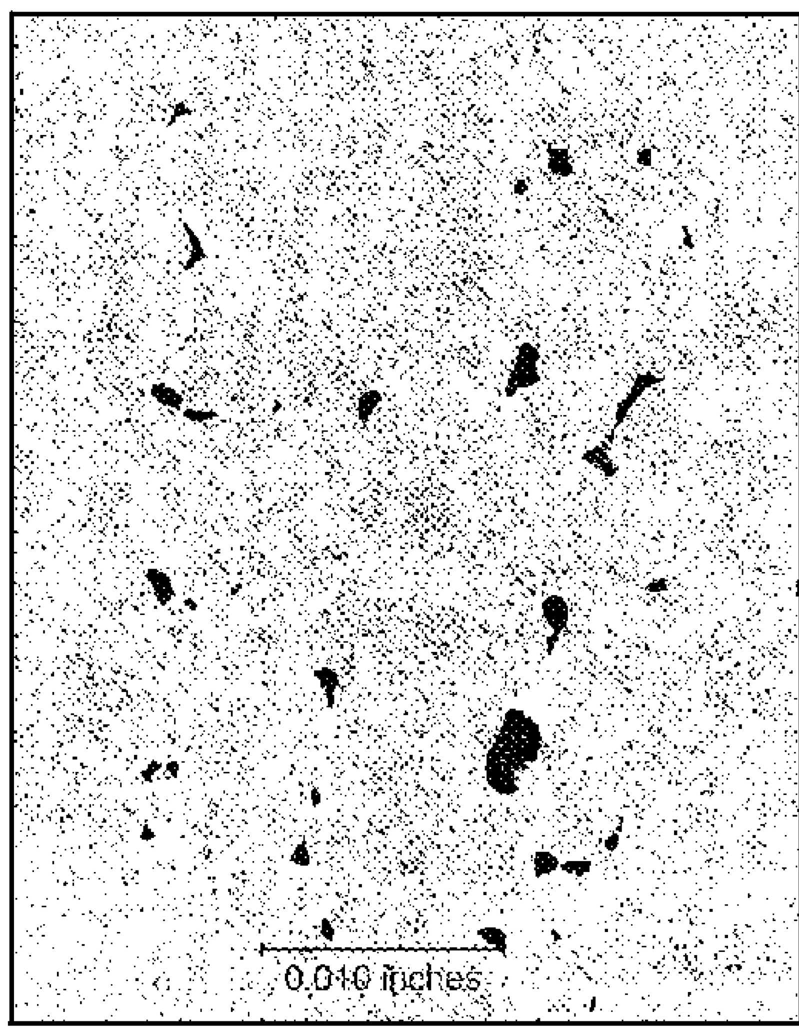


FIG. 12A

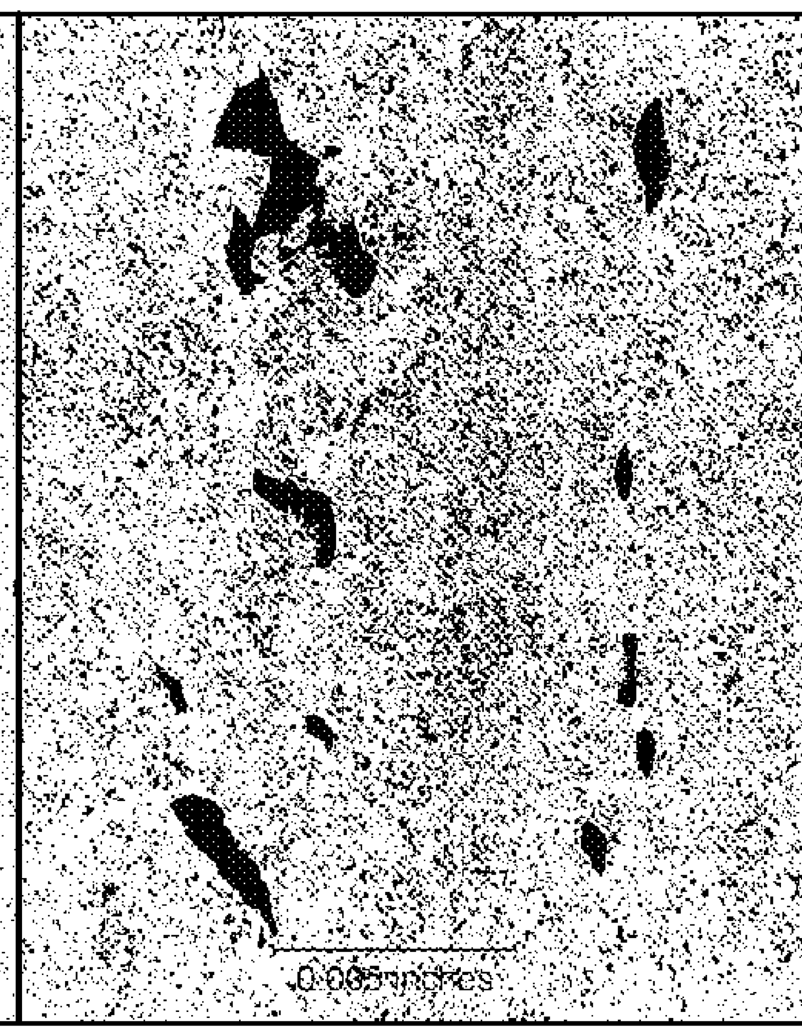


FIG. 12B

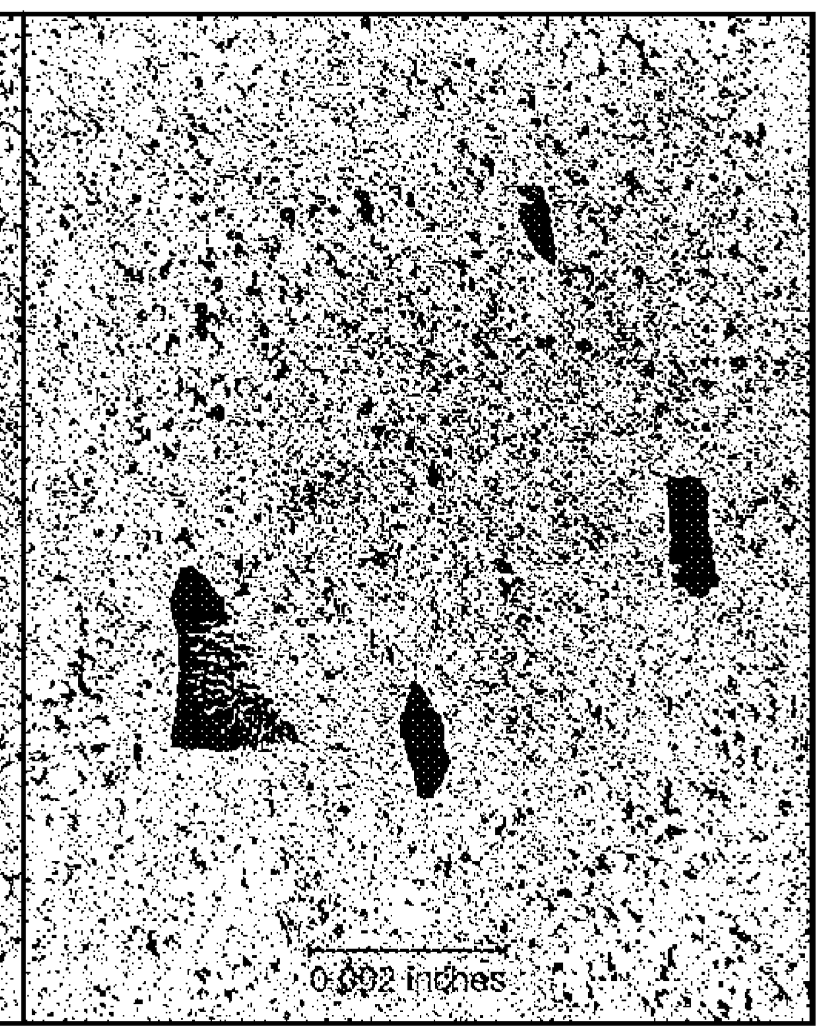


FIG. 12C

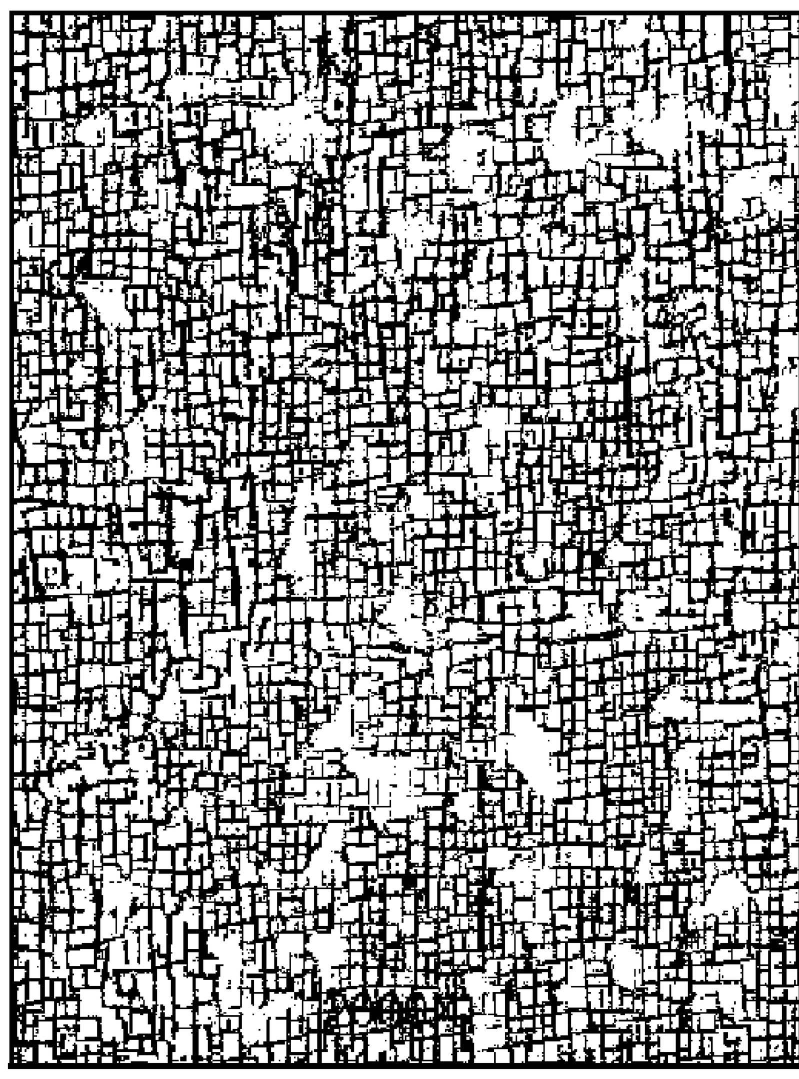


FIG. 13A

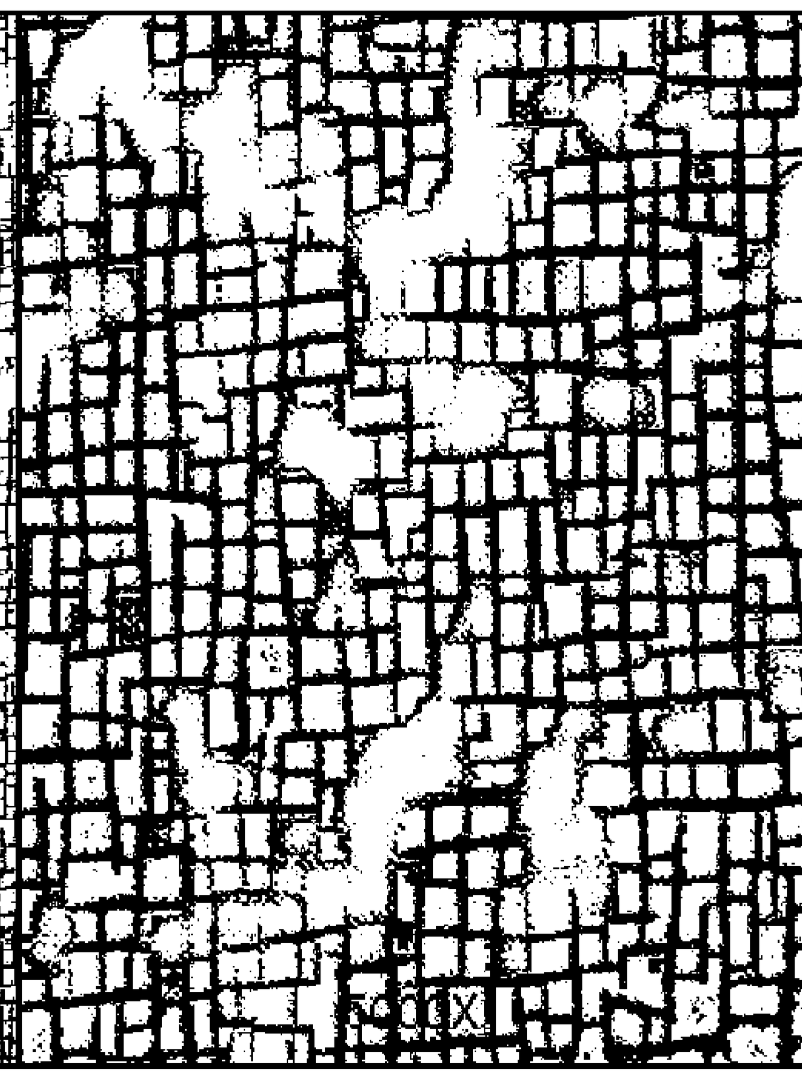


FIG. 13B

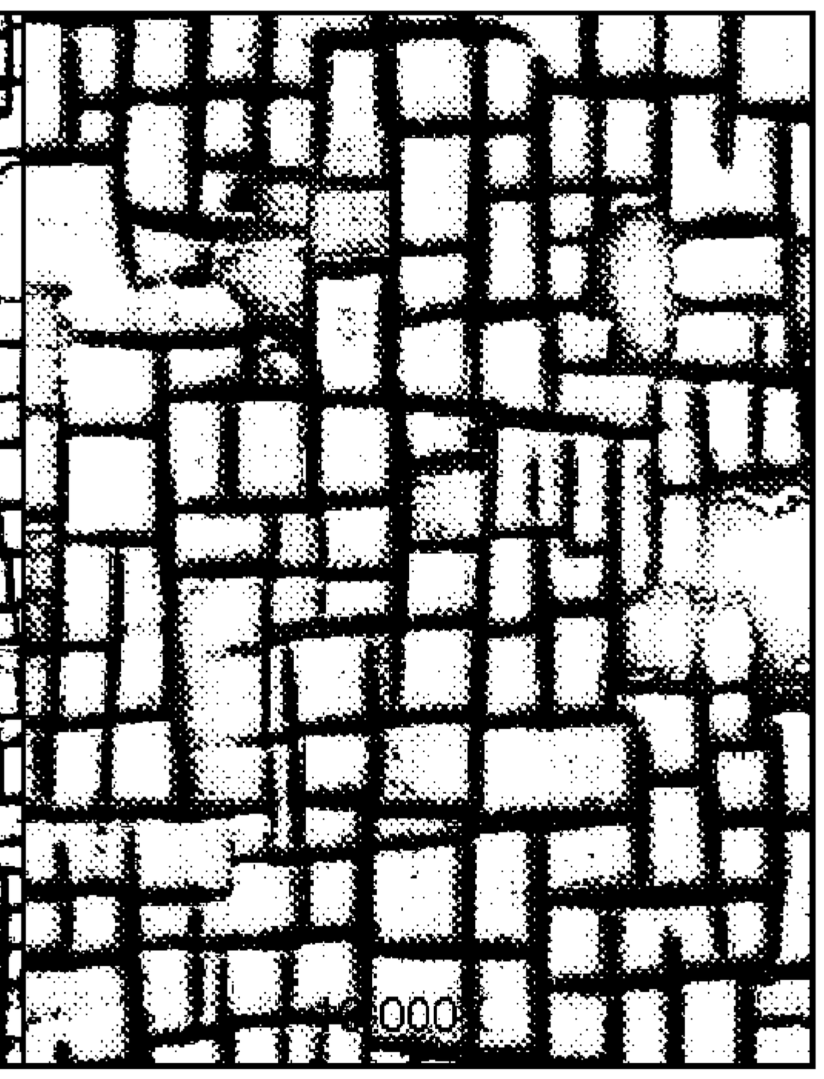


FIG. 13C

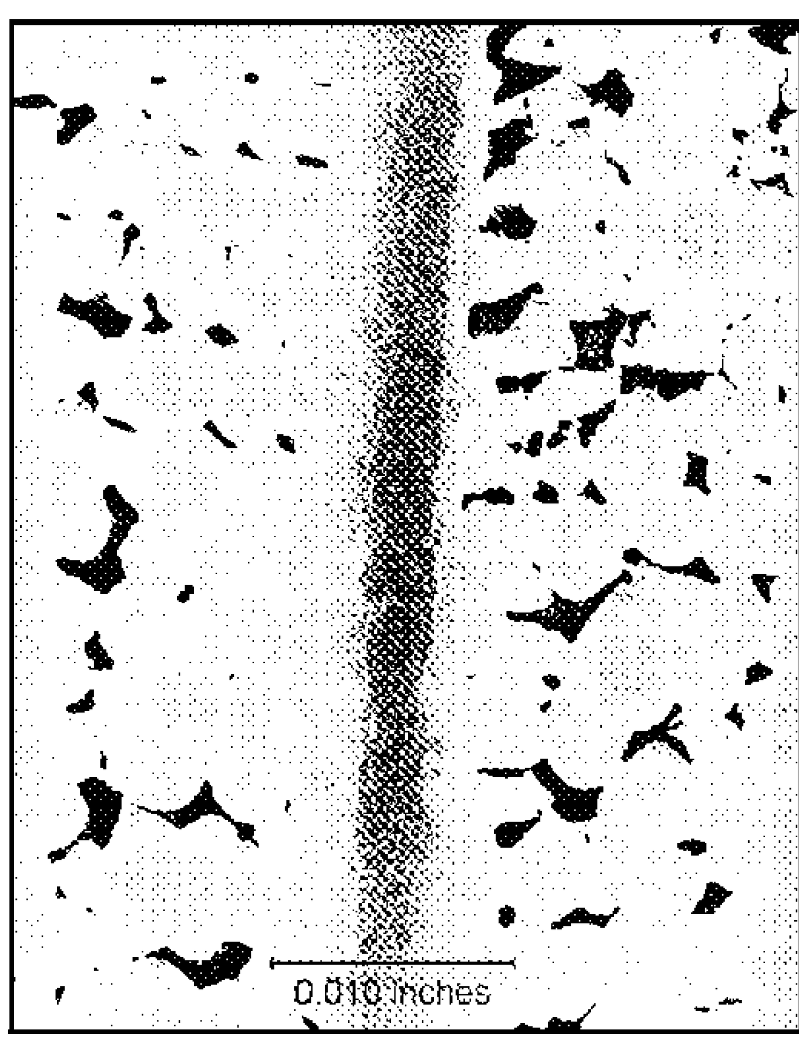


FIG. 14A

FIG. 14B

FIG. 14C

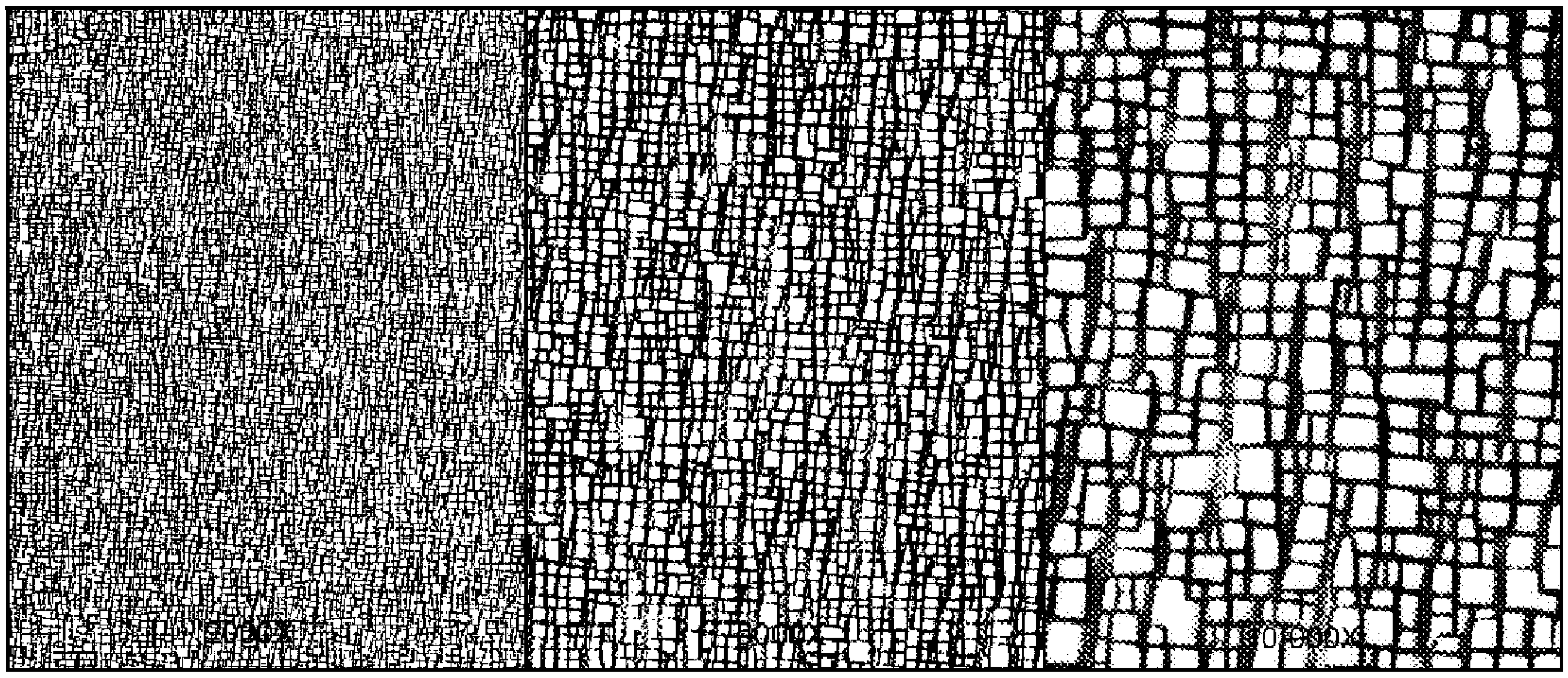


FIG. 15A FIG. 15B FIG. 15C

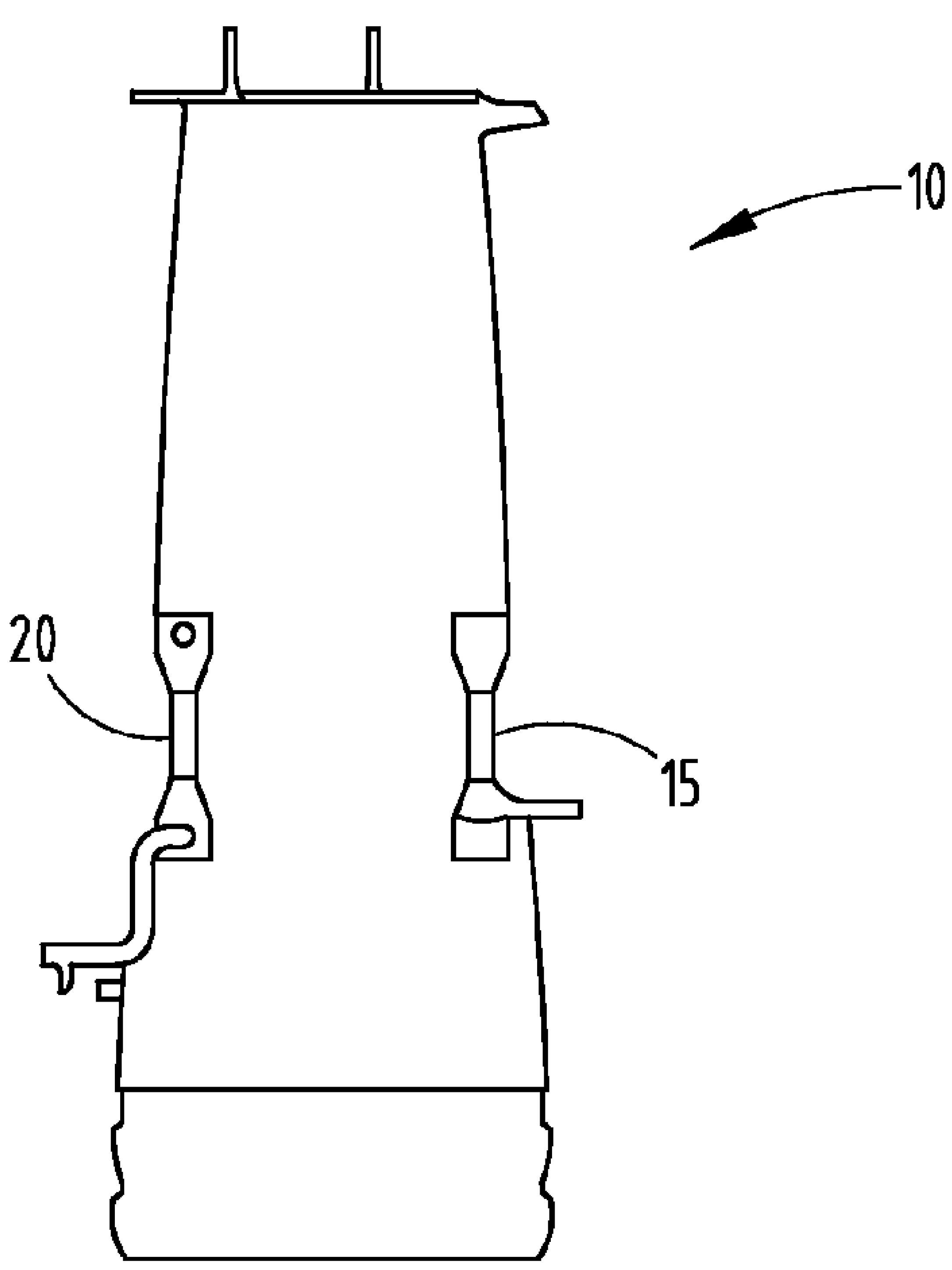


FIG. 16

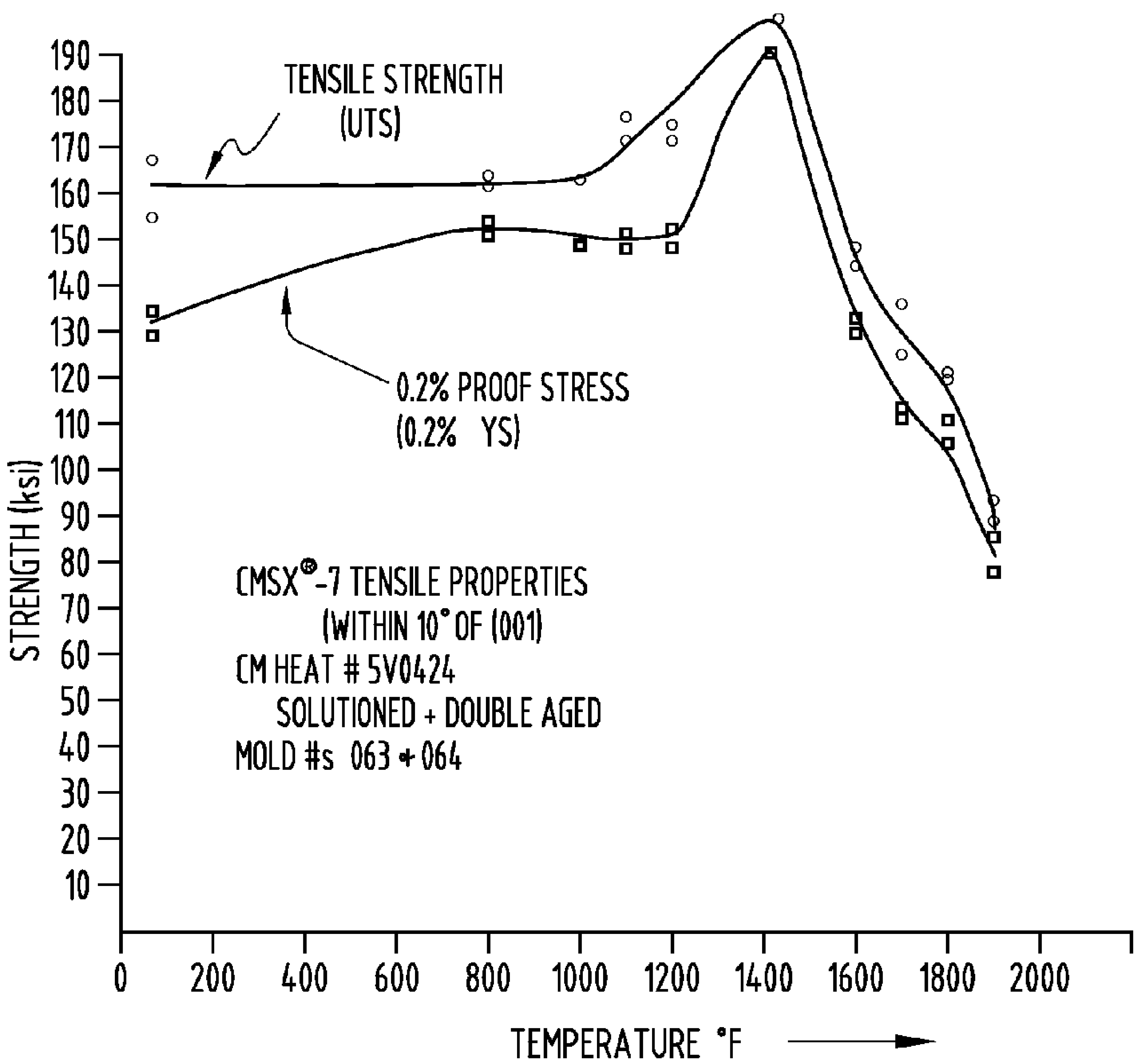

TENSILE STRENGTH
(UTS)
0.2% PROOF STRESS
(0.2% YS)
CMSX®-7 TENSILE PROPERTIES
(WITHIN 10° OF (001)
CM HEAT # 5V0424
SOLUTIONED + DOUBLE AGED
MOLD #s 063 + 064
STRENGTH (ksi)
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TEMPERATURE °F

FIG. 17

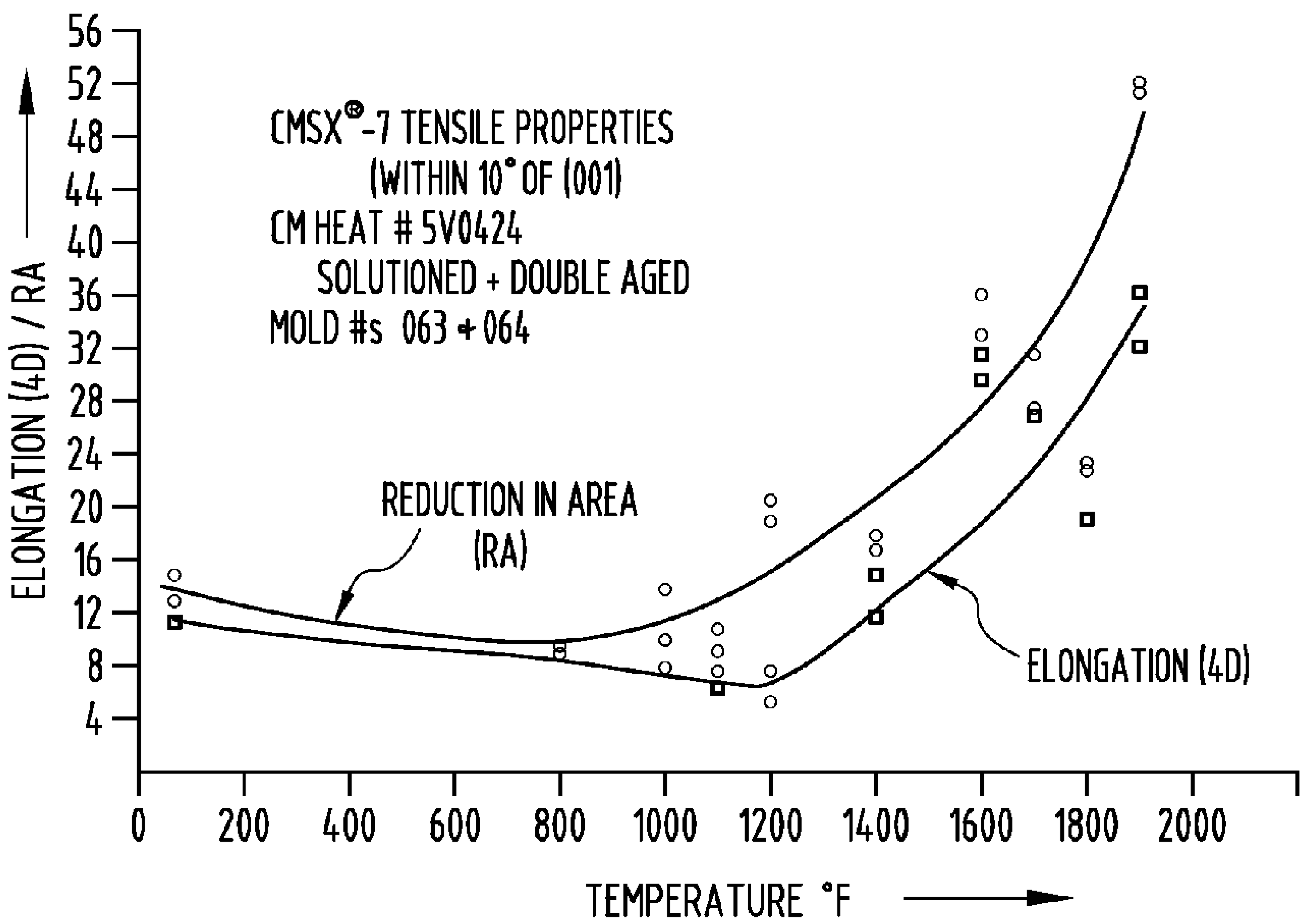

CMSX®-7 TENSILE PROPERTIES
(WITHIN 10° OF (001)
CM HEAT # 5V0424
SOLUTIONED + DOUBLE AGED
MOLD #s 063 + 064
REDUCTION IN AREA
(RA)
ELONGATION (4D)
ELONGATION (4D) / RA
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
200
400
600
800
1000
1200
1400
1600
1800
2000
TEMPERATURE °F

FIG. 18

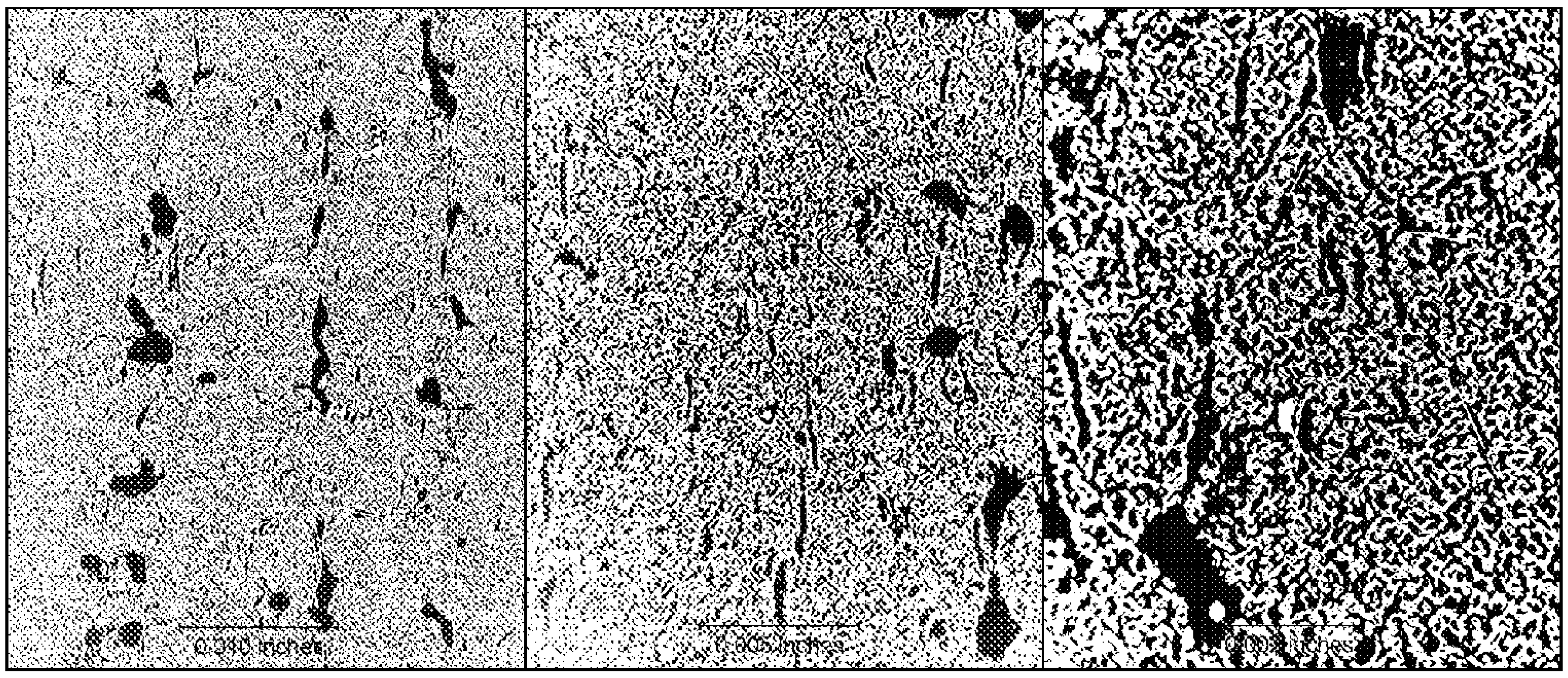


FIG. 19A FIG. 19B FIG. 19C

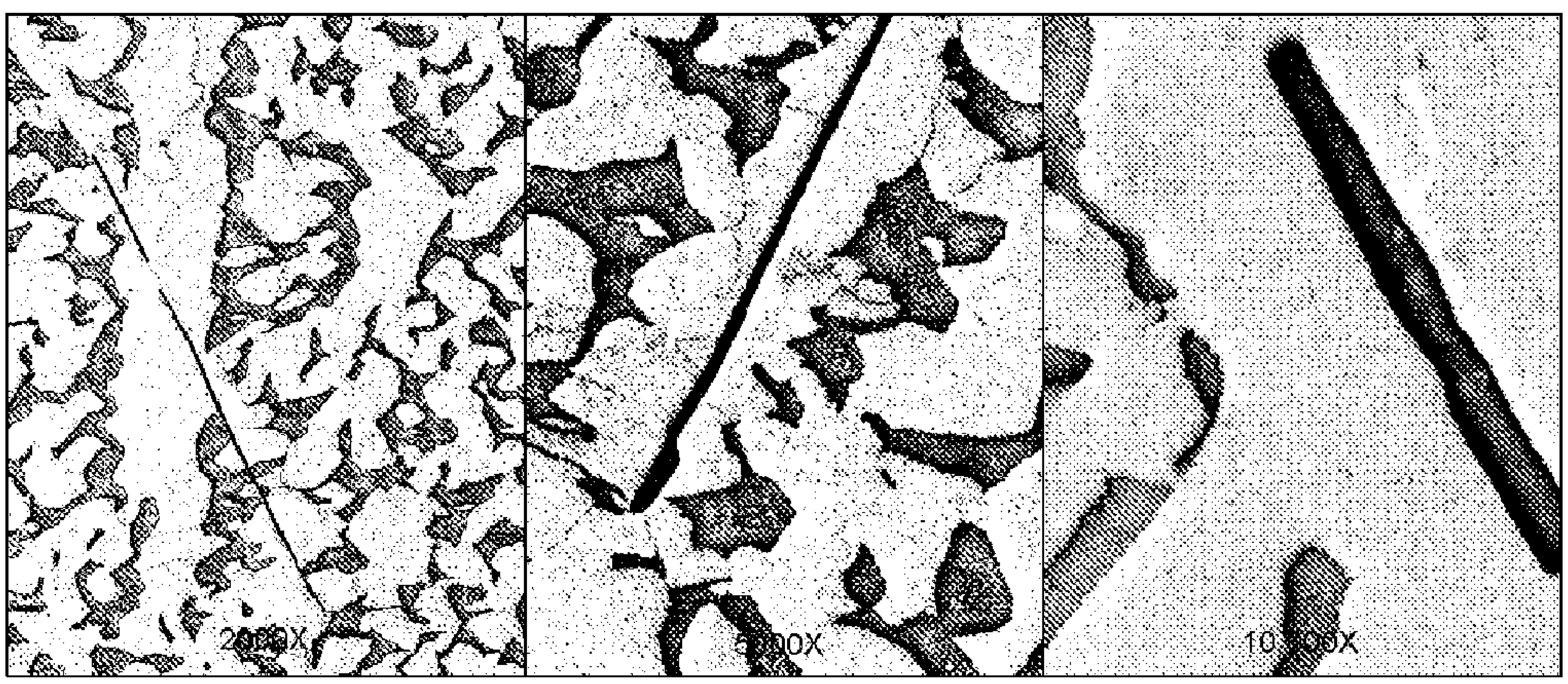


FIG. 20A FIG. 20B FIG. 20C

RHENIUM-FREE SINGLE CRYSTAL SUPERALLOY FOR TURBINE BLADES AND VANE APPLICATIONS

FIELD

[0001] Disclosed are single crystal nickel-base superalloys exhibiting excellent high temperature creep resistance, while being substantially free of rhenium, without deleteriously affecting other relevant characteristics.

BACKGROUND

[0002] Because of a worldwide growing demand for products that have customarily required substantial quantities of relatively scarce metal elements, both the demand and prices of rare metal elements have sharply increased. As a result, manufacturers are searching for new technologies that will reduce or eliminate the need for these metal elements.

[0003] Rhenium is an example of a truly rare metal that is important to various industries. It is recovered in very small quantities as a by-product of copper-molybdenum and copper production. In addition to its high cost, use of rhenium presents a supply chain risk of both economic and strategic consequence.

[0004] Rhenium has been widely employed in the production of nickel-base superalloys used to cast single crystal gas turbine components for jet aircraft and power generation equipment. More specifically, rhenium is used as an alloying additive in advanced single crystal superalloys for turbine blades, vanes and seal segments, because of its potent effect at slowing diffusion and thus slowing creep deformation, particularly at high temperatures (e.g., in excess of 1,000 degrees C.) for sustained periods of time. High temperature creep resistance is directly related to the useful service life of gas turbine components and engine performance such as power output, fuel burn and carbon dioxide emissions.

[0005] Typical nickel-base superalloys used for single crystal castings contain from about 3% rhenium to about 7% rhenium by weight. Although rhenium has been used as only a relatively minor additive, it has been regarded as critical to single crystal nickel-base superalloys to inhibit diffusion and improve high temperature creep resistance, it adds considerable to the total cost of these alloys.

[0006] From the foregoing discussion, it is apparent that it would be extremely desirable to develop single crystal nickel-base superalloys that exhibit excellent high temperature creep resistance, while reducing or eliminating the need for rhenium additions, and while retaining other desirable properties such as good castability and phase stability.

SUMMARY

[0007] The rhenium-free single crystal nickel-base superalloys disclosed herein rely on, among other things, balancing the refractory metal elements (tantalum, tungsten and molybdenum) at a total amount of about 17% to 20% in order to achieve good creep-rupture mechanical properties along with acceptable alloy phase stability, in particular, ensuring freedom from excessive deleterious topological close-packed (TCP) phases that are rich in tungsten, molybdenum and chromium, while substantially eliminating rhenium from the alloy.

[0008] It has been discovered that a rhenium-free single crystal nickel-base superalloy exhibiting excellent high temperature creep resistance and other properties well suited for used in casting gas turbine components can be achieved in an alloy composition containing 5.60% to 5.85% aluminum by weight, 9.4% to 9.9% cobalt by weight; 5.0% to 6.0% chromium by weight, 0.08% to 0.35% hafnium by weight, 0.50% to 0.70% molybdenum by weight, 8.0% to 9.0% tantalum by weight, 0.60% to 0.90% titanium by weight, 8.5% to 9.8% tungsten by weight, and the balance comprising nickel and minor amounts of incidental elements, the total amount of incidental elements being substantially less than 1% by weight.

[0009] In accordance with certain embodiments, the incidental elements of the alloy is controlled to maximums of 100 ppm carbon, 0.04% silicon, 0.01% manganese, 3 ppm sulfur, 30 ppm phosphorous, 30 ppm boron, 0.1% niobium, 150 ppm zirconium, 0.15% rhenium, 0.01% copper, 0.15% iron, 0.1% vanadium, 0.1% ruthenium, 0.15% platinum, 0.15% palladium, 200 ppm magnesium, 5 ppm nitrogen, and 5 ppm oxygen, with each of any other incidental elements being present as a trace element as a maximum of about 25 ppm.

[0010] In accordance with certain embodiments, the trace elements in the incidental impurities of the disclosed nickel-base superalloys is controlled to maximums of 2 ppm silver, 0.2 ppm bismuth, 10 ppm gallium, 25 ppm calcium, 1 ppm lead, 0.5 ppm selenium, 0.2 ppm tellurium, 0.2 ppm thallium, 10 ppm tin, 2 ppm antimony, 2 ppm arsenic, 5 ppm zinc, 2 ppm mercury, 2 ppm cadmium, 2 ppm germanium, 2 ppm gold, 2 ppm indium, 20 ppm sodium, 10 ppm potassium, 10 ppm barium, 30 ppm phosphorous, 2 ppm uranium, and 2 ppm thorium.

[0011] In accordance with certain embodiments in which enhanced oxidation resistance and/or coating and thermal barrier coating (TBC) life are desired, sulfur is present at a maximum amount of 0.5 ppm, and lanthanum and yttrium are added to target an amount of total lanthanum and yttrium of from about 5 ppm to about 80 ppm in single crystal components cast from the alloy.

[0012] In accordance with certain embodiments used for large industrial gas turbine (IGT) single crystal component applications requiring low angle boundary (LAB) strengthening up to 12 degrees, carbon is added in an amount from about 0.02% to about 0.05% by weight and boron is added in an amount from about 40 ppm to about 100 ppm.

[0013] In addition to achieving excellent high temperature creep resistance in a substantially rhenium-free composition, certain embodiments of the disclosed single crystal nickel-base superalloys have a desirably not excessive density that is about 8.8 gms/cc or less, such as 8.79 gms/cc (kg/dm^3).

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIGS. **1**A, **1**B and **1**C are optical micrographs showing the fully heat treated microstructure of castings of a disclosed embodiment (LA-11753, CMSX-7, test bar #C912, fully heat treated, primary age 2050° F./4 hours).

[0015] FIGS. **2**A, **2**B and **2**C are scanning electron micrographs of the microstructure of fully heat treated castings from embodiments disclosed herein (LA-11753, CMSX-7, test bar #C912, fully heat treated, primary age 2050° F./4 hours).

[0016] FIGS. **3**, **4** and **5** are Larson-Miller stress-rupture graphs showing the surprisingly good creep strength and/or stress-rupture life properties of single crystal test bars and turbine blade castings made from the disclosed alloys.

[0017] FIGS. **6**A, **6**B and **6**C are optical micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #D912, 2050° F./15 ksi/141.6 hours, gage area).

[0018] FIGS. **7**A, **7**B and **7**C are scanning electron micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #D912, 2050° F./15 ksi/141.6 hours, gage area).

[0019] FIGS. **8**A, **8**B and **8**C are optical micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11807, CMSX-7, mini-flat #53701Y-F, 2000° F./12 ksi/880.0 hours, gage area).

[0020] FIGS. **9**A, **9**B and **9**C are scanning electron micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11807, CMSX-7, mini-flat #53701Y-F, 2000° F./12 ksi/880.0 hours, gage area).

[0021] FIGS. **10**A, **10**B and **10**C are optical micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #B913, 1800° F./36 ksi/151.1 hours, gage area).

[0022] FIGS. **11**A, **11**B and **11**C are scanning electron micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #B913, 1800° F./36 ksi/151.1 hours, gage area).

[0023] FIGS. **12**A, **12**B and **12**C are optical micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #A912, 1562° F./94.4 ksi/100.9 hours, gage area).

[0024] FIGS. **13**A, **13**B and **13**C are scanning electron micrographs showing the post-test phase stability of the disclosed alloys, which exhibit excellent phase stability and no TCP phases (LA-11772, CMSX-7, test bar #A912, 1562° F./94.4 ksi/100.9 hours, gage area).

[0025] FIGS. **14**A, **14**B and **14**C are optical micrographs showing the fully heat treated microstructures of CMSX-7 MOD B single crystal test bars.

[0026] FIGS. **15**A, **15**B and **15**C are scanning electron micrographs showing the fully heat treated microstructures of CMSX-7 MOD B single crystal test bars.

[0027] FIG. **16** is a drawing in cross section of a single crystal solid turbine blade cast from an alloy as disclosed herein which has the facility to machine both mini-bar and mini-flat specimens for machined-from-blade (MFB) stress-rupture testing.

[0028] FIGS. **17** and **18** show the tensile properties of the alloys versus test temperature.

[0029] FIGS. **19**A, **19**B and **19**C are optical micrographs showing post test microstructures from a long term, high temperature stress-rupture test of an alloy as disclosed herein (LA-11891, CMSX-7 MOD. B, test bar #M923, 2000° F./12 ksi/1176.5 hours).

[0030] FIGS. **20**A, **20**B and **20**C are scanning electron micrographs showing post test microstructures from a long term, high temperature stress-rupture test of an alloy as disclosed herein (LA-11891, CMSX-7 MOD. B, test bar #M923, 2000° F./12 ksi/1176.5 hours).

DETAILED DESCRIPTION

[0031] The alloys disclosed herein will be referred to as "CMSX®-7" alloys. This is the designation that will be used commercially, the expression "CMSX" being a registered trademark of the Cannon-Muskegon Corporation used in connection with the sale of a family or series of nickel-base single crystal (SX) superalloys.

[0032] The alloys disclosed herein are alternatively described as being rhenium-free, or substantially free of rhenium. As used herein, these terms means that the alloys do not contain any added rhenium and/or that the amount of rhenium present in the alloy is a maximum of 0.15% by weight.

[0033] Unless otherwise indicated, all percentages are by weight, and all amounts in parts per million (ppm) refer to parts per million by weight based on the total weight of the alloy composition.

[0034] Single crystal superalloys and castings have been developed to exhibit an array of outstanding properties including high temperature creep resistance, long fatigue life, oxidation and corrosion resistance, solid solution strengthening, with desired casting properties and low rejection rates, and phase stability, among others. While it is possible to optimize a single additive alloying elements for a particular property, the effects on other properties are often extremely unpredictable. Generally, the relationships among the various properties and various elemental components are extremely complex and unpredictable such that it is surprising when a substantial change can be made to the composition without deleteriously affecting at least certain essential properties.

[0035] With the embodiments disclosed herein, refractory metal elements (tantalum, tungsten and molybdenum) were maintained at a total amount of from about 17% to about 20% by weight, while balancing the amounts of the refractory elements to achieve good creep-rupture mechanical properties along with acceptable alloy phase stability (freedom from excessive deleterious topological close-packed (TCP) phase—normally tungsten, molybdenum and chromium rich in this type of alloy). Chromium and cobalt were also adjusted to ensure the required phase stability. The high amount of tantalum (approximately 8%) was selected to provide excellent single crystal castability, such as freedom from "freckling" defects. The amount of titanium (approximately 0.8%) and tantalum (approximately 0.8%) were adjusted to provide low negative γ/γ' mismatch for high temperature creep strength and acceptable room temperature density (e.g., about 8.8 gms/cc, such as 8.79 gms/cc). Aluminum, titanium and tantalum were adjusted to attain a suitable γ' volume fraction (Vf), while the combination of aluminum, molybdenum, tantalum and titanium were selected to provide good high temperature oxidation resistance properties. The amount of hafnium addition was selected for coating life attainment at high temperatures.

[0036] Typical chemistry for the alloys disclosed and claimed herein are listed in Table 1. However, there are certain minor variations. First, in order to achieve enhanced oxidation resistance and/or enhanced thermal barrier coating life, it is desirable to add lanthanum and/or yttrium in amounts such that the total of lanthanum and yttrium is targeted to provide from about 5 to 80 ppm in the single crystal castings made from the alloys. As another variation, in the case of large industrial gas turbine (IGT) single crystal applications where low angle boundary (LAB) strengthening is required up to 12 degrees, carbon and boron additions are targeted in the range from about 0.02% to 0.05% and 40-100 ppm, respectively.

[0037] The invention will be described with respect to certain illustrative, non-limiting embodiments that will facilitate a better understanding.

[0038] A 400 lb 100% virgin initial heat of CMSX®-7 alloy was melted in January 2011 in the CM V-5 Consarc VIM furnace using aim chemistry to CM KH Jan. 3, 2011 (CM CRMP #81-1700 Issue 1). The heat (5V0424) chemistry is shown in Table 2.

[0039] Two molds (#s 912 and 913) of SX NNS DL-10 test bars were cast to CMSX-4® casting parameters by Rolls-Royce Corporation (SCFO). DL-10 test bar yield at 23 fully acceptable out of a total 24 cast was excellent. A mold (#53701) of solid HP2 turbine blades were also SX cast by SCFO using CMSX-4® casting parameters with typical casting yields for this production component.

[0040] These DL-10 test bars and turbine blades were solutioned/homogenized+double aged heat treated at CM as follows—based on solutioning/homogenization studies on CMSX®-7 test bars.

Solution+Homogenization

[0041] 2 hrs/2340° F. (1282° C.)+2 hrs/2360° F. (1293° C.)

[0042] +4 hrs/2380° F. (1304° C.)+4 hrs/2390° F. (1310° C.)

[0043] +12 hrs/2400° F. (1316° C.) AC—ramping up at 1° F./min. between steps

[0044] Double Age

[0045] 4 hrs/2050° F. (1121° C.) A +20 hrs/1600° F. (871° C.) AC

[0046] Acceptable microstructure attainment is evident in FIGS. **1-2**—complete γ' solutioning, some remnant γ/γ' eutectic, no incipient melting and approximately 0.5 μm average cubic, aligned γ', indicating appropriate γ/γ' mis-match and γ/γ'inter-facial chemistry, following the 4 hr/2050° F. (1121° C.) high temperature age.

[0047] Creep—and stress-rupture specimens were low stress ground and tested by Joliet Metallurgical Labs, with the results to date shown in Table 3 and Table 4. Larson-Miller stress-rupture graphs (FIGS. **3**, **4** & **5**) show CMSX®-7 has superior and surprisingly good creep strength/stress-rupture life properties, including machined-from-blade (MFB) 0.070" Ø mini-bar results, compared to CMSX-2/3® alloy (zero Re) up to approximately 1900° F. (1038° C.), with similar properties at 2050° F. (1121° C.). All these properties are surprisingly similar to Rene' N-5 (3% Re) and Rene' N-515 (1.5% Re) alloys (Published GE data) [JOM 62 No 1, pgs 55-57 January 2010]. MFB stress-rupture testing was performed on single crystal solid turbine blades **10** (FIG. **16**) cast from alloys as disclosed herein which have facility to machine mini-bars **15** and mini-flat specimens **20**.

[0048] Phase stability is surprisingly good with absolutely no TCP phases apparent in the post-test creep/stress rupture bars examined to date (FIGS. **6-13** inclusive).

[0049] Burner rig dynamic, cyclic oxidation and hot corrosion (sulfidation) testing is currently scheduled at a major turbine engine company. The MFB 0.020" thick gage mini-flat results at 12 ksi/2000° F. (Table 4, FIG. **5**) indicate good bare high temperature oxidation resistance for this alloy.

[0050] CMSX-7 Tensile Properties

[0051] The alloy shows very high tensile strength (up to 200 ksi (1379 MPa) UTS at 1400° F. (760° C.)) and 0.2% proof stress (up 191 ksi (1318 MPa) at the same temperature and good ductility (Table 5, FIGS. **17** & **18**). The exceptionally high UTS and 0.2% PS at 1400° F. (760° C.) indicates strain hardening at this temperature, possibly due to further secondary or tertiary γ' precipitation in the γ channels at this temperature impeding dislocation movement —the ductility at this maximum strength level is in the range of 13% elongation (4D) and 17% reduction in area (RA).

TABLE 1

CHEMISTRY (WT %/ppm) SPECIFICATIONS CMSX ®-7 ALLOY

Aero engine Applications

C	100 ppm	Ti	.60-.90
Si	.04% Max	W	8.5-9.8
Mn	.01% Max	Zr	150 ppm Max
S	3 ppm Max	Re	.15% Max
Al	5.60-5.85	Cu	.01% Max
B	30 ppm Max	Fe	.15% Max
Cb (Nb)	.10% Max	V	.10% Max
Co	9.4-9.9	Ru	.10% Max
Cr	5.0-6.0	Pt	.15% Max
Hf	.08-.35	Pd	.15% Max
Mo	.50-.70	Mg	200 ppm Max
Ni	Balance	[N]	5 ppm Max
Ta	8.0-9.0	[O]	5 ppm Max

Enhanced oxidation resistance/coating and thermal barrier coating (TBC) life

S	0.5 ppm max
La + Y	5-80 ppm (In the SX castings).

Industrial Gas Turbine (IGT) SX Applications

Low angle boundary (LAB) Strengthened up to 12°.

C	0.02-0.05% Max
B	40-100 ppm Max

TRACE ELEMENT CONTROLS - ALL APPLICATIONS

Ag	2 ppm Max	Hg	2 ppm Max
Bi	.2 ppm Max	Cd	2 ppm Max
Ga	10 ppm Max	Ge	2 ppm Max
Ca	25 ppm Max	Au	2 ppm Max
Pb	1 ppm Max	In	2 ppm Max
Se	.5 ppm Max	Na	20 ppm Max
Te	.2 ppm Max	K	10 ppm Max
Tl	.2 ppm Max	Ba	10 ppm Max
Sn	10 ppm Max	P	30 ppm Max
Sb	2 ppm Max	U	2 ppm Max
As	2 ppm Max	Th	2 ppm Max
Zn	5 ppm Max		

Density: 8.79 gms/cc.

TABLE 2

HEAT #5V0424 CMSX ®-7 - 100% VIRGIN CHEMISTRY (WT ppm/%)

C	17 ppm	Re	<.05
Si	<.02	Cu	<.001
Mn	<.001	Fe	.012
S	1 ppm	V	<.005
Al	5.80	Ru	<.01
B	<20 ppm	Pt	<.001
Cb (Nb)	<.05	Pd	<.001
Co	9.7	Mg	<100 ppm
Cr	5.8	[N]	3 ppm
Hf	.29	[O]	2 ppm
Mo	.60	Y	<.001

TABLE 2-continued

HEAT #5V0424 CMSX ®-7 - 100%
VIRGIN CHEMISTRY (WT ppm/%)

Ni	Balance	La	<.001
Ta	8.6	Ce	<.002
Ti	.82		
W	9.0		
Zr	<25 ppm		

Ag	<.4 ppm
Bi	<.2 ppm
Ga	<10 ppm
Ca	<25 ppm
Pb	<.5 ppm
Se	<.5 ppm
Te	<.2 ppm
Tl	<.2 ppm
Sn	<2 ppm
Sb	<1 ppm
As	<1 ppm
Zn	<1 ppm
Hg	<2 ppm
Cd	<.2 ppm
Ge	<1 ppm
Au	<.5 ppm
In	<.2 ppm
Na	<10 ppm
K	<5 ppm
Ba	<10 ppm
P	6 ppm
U	<.5 ppm
Th	<1 ppm

TABLE 3

CMSX-7 Heat 5V0424
Molds 912/913 (DL-10 s) - RR SCFO [Indy] -
LA11753 (Joliet 8935/CM-354)
K912/L912 - LA 11773 (Joliet 8979/CM-356)
Fully Heat Treated - Solution + double age - 2050° F. primary age

Creep-Rupture

Test Condition	ID	Rupture Life, hrs	% Elong	% RA	Time to 1% Creep	Time to 2% Creep
1562° F./94.4 ksi	A912	100.9	22.4	28.8	5.9	19.8
[850° C./651 MPa]	A913	100.8	18.4	27.3	7.0	22.3
1800° F./36.0 ksi	B912	147.2	41.8	14.7	58.4	71.1
[982° C./248 MPa]	B913	151.1	44.6	49.6	58.4	70.4
1922° F./27.6 ksi	C912	53.9	43.6	46.9	19.3	24.4
[1050° C./190 MPa]	C913	46.0	37.1	49.7	15.8	20.6
1950° F./18.0 ksi [1066° C./124 MPa]	L912	224.9	37.0	62.3	92.4	112.3
2000° F./12.0 ksi [1093° C./83 MPa]	K912	860.3	22.1	54.5	538.1	607.2

Stress-Rupture

Test Condition	ID	Rupture Life, hrs	% Elong	% RA
2050° F./15.0 ksi	D912	141.6	32.4	52.6
[1121° C./103 MPa]	E912	130.2	31.4	55.0

Machining and Testing Source: Joliet Metallurgical Laboratory

TABLE 4

CMSX ®-7 Heat 5V0424
Mold 53701 - HP2 Solid Turbine Blades RR
SCFO [Indy] - LA11773 (Joliet 8980/CM-357)
Fully Heat Treated - Solution + double age - 2050° F. primary age

MFB (LLE)
Stress-Rupture
Mini Bars [0.070" Ø Gage, shown in FIG. 16]

Test Condition	ID	Rupture Life, hrs	% Elong	% RA
1562° F./72.5 ksi [850° C./500 MPa]	53701U-B	783.4	33.3	28.9
1600° F./65.0 ksi [871° C./448 MPa]	53701V-B	437.9	32.8	33.7
1800° F./40.0 ksi [982° C./276 MPa]	53701S-B	84.1	39.5	47.8
1850° F./38.0 ksi [1010° C./262 MPa]	53701T-B	43.2	38.5	37.8
1900° F./25.0 ksi [1038° C./172 MPa]	53701Y-B	105.8	36.1	28.5
1904° F./21.0 ksi [1040° C./145 MPa]	53701Z-B	238.4	59.3	44.5

MFB (LTE)
Mini Flats [0.020" Thick Gage, shown in FIG. 16]

Test Condition	ID	Rupture Life, hrs	% Elong
1800° F./30.0 ksi	53701S-F	387.3	42.7
[982° C./207 MPa]	53701T-F	344.4	35.0
1904° F./21.0 ksi	53701U-F	219.8	38.1
[1040° C./145 MPa]	53701V-F	189.5	33.3
2000° F./12.0 ksi	53701Y-F	880.0	32.4
[1093° C./83 MPa]	53701Z-F	578.8	13.9

Machining and Testing Source: Joliet Metallurgical Laboratory

TABLE 5

CMSX-7 - Heat 5V0424
Molds 063/064 - RR SCFO [Indy] - LA 11753 (Joliet 8935/CM-354)
Fully Heat Treated - Solution + Double Age - 2050° F. Primary Age

TENSILE TEST RESULTS

Test Temperature	ID	0.2% PS (ksi)	UTS (ksi)	% Elona (4D)	% RA
70° F. (21° C.)	A063	135.1	154.6	11.4	13.1
	A064	129.1	168.1	11.3	15.3
800° F. (430° C.)	B063	154.2	163.8	9.1	9.5
	B064	151.6	162.2	9.0	9.8
1000° F. (538° C.)	K063	149.7	163.3	8.0	10.0
	K064	148.6	163.2	8.0	13.9
1100° F. (593° C.)	L063	149.6	172.0	7.7	10.7
	L064	151.9	177.1	6.5	9.3
1200° F. (649° C.)	M063	153.8	175.5	7.8	19.2
	M064	149.0	172.0	5.4	20.4
1400° F. (760° C.)	N063	190.4	198.9	14.9	16.8
	N064	191.7	199.7	12.0	17.9
1600° F. (871° C.)	P063	131.3	148.4	31.9	33.2
	P064	133.9	145.3	29.8	36.1
1700° F. (927° C.)	R063	112.8	136.9	27.5	27.7
	R064	115.0	126.4	27.0	31.7
1800° F. (982° C.)	Y063	112.4	123.3	19.5	23.0
	W064	106.9	120.3	23.6	23.8
1900° F. (1038° C.)	Z063	88.3	94.6	32.5	52.2
	X064	78.9	90.2	36.6	51.4

[100 ksi = 690 Mpa]
Machining & Testing Source: Joliet Metallurgical Laboratory

TABLE 6

HEAT #5V0459 CMSX ®-7 Mod B - 100% VIRGIN CHEMISTRY (WT ppm/%)			
C	9 ppm	Re	<.05
Si	<.02	Cu	<.001
Mn	<.001	Fe	.015
S	1 ppm	V	<.005
Al	5.780	Ru	<.01
B	<25 ppm	Pt	<.001
Cb	<.05	Pd	<.001
(Nb)		Mg	<100 ppm
Co	9.7	[N]	1 ppm
Cr	5.6	[O]	1 ppm
Hf	.30	Y	<.001
Mo	.59	La	<.001
Ni	Balance	Ce	<.002
Ta	8.4		
Ti	.70		
W	9.3		
Zr	<25 ppm		

Ag	<.4 ppm
Bi	<.2 ppm
Ga	<10 ppm
Ca	<25 ppm
Pb	<.5 ppm
Se	<.5 ppm
Te	<.2 ppm
Tl	<.2 ppm
Sn	<2 ppm
Sb	<1 ppm
As	<1 ppm
Zn	<1 ppm
Hg	<2 ppm
Cd	<.2 ppm
Ge	<1 ppm
Au	<.5 ppm
In	<.2 ppm
Na	<10 ppm
K	<5 ppm
P	8 ppm
U	<.5 ppm
Th	<1 ppm

TABLE 7

CMSX-7 MOD B - Heat 5V0459
Molds 923/924 - (DL-10 s) - RR SCFO [Indy] -
LA11834 (Joliet 9156/CM-368) [DL-10s]
Fully Heat Treated - Solution + double age

Creep-Rupture

Test Condition	ID	Rupture Life, hrs	% Elong	% RA	1% Creep	2% Creep
1562° F./72.5 ksi	A923	972.7	19.6	25.2	298.3	463.7
[850° C./500 MPa]	H923	861.8	20.6	27.6	275.7	411.2
1600° F./65.0 ksi	B923	667.4	21.8	26.5	224.6	323.0
[871° C./448 MPa]	R924	670.4	19.8	31.3	262.8	363.8
1800° F./36.0 ksi	C923	139.2	37.9	45.6	56.2	68.0
[982° C./248 MPa]	N924	151.5	31.6	38.0	64.6	77.2
1800° F./40.0 ksi	D923	97.4	34.8	41.5	39.4	48.0
[982° C./276 MPa]	M24	106.3	28.8	33.7	45.3	55.2
1850° F./38.0 ksi	E923	51.7	34.3	35.2	21.1	25.6
[1010° C./262 MPa]	L924	54.1	36.5	36.6	21.2	26.0
1900° F./25.0 ksi	J923	103.0	25.1	43.5	39.5	49.3
[1038° C./172 MPa]	H924	111.2	27.6	40.2	38.6	51.1
1904° F./21.0 ksi	K923	240.2	31.0	47.1	90.6	112.9
[1040° C./145 MPa]	E924	245.7	43.4	46.7	86.5	109.1
1950° F./18.0 ksi	L923	260.5	27.4	37.5	86.0	112.4
[1066° C./124 MPa]	D924	219.1	38.4	41.7	79.8	101.5

TABLE 7-continued

CMSX-7 MOD B - Heat 5V0459
Molds 923/924 - (DL-10 s) - RR SCFO [Indy] -
LA11834 (Joliet 9156/CM-368) [DL-10s]
Fully Heat Treated - Solution + double age

Stress-Rupture

Test Condition	ID	Rupture Life, hrs	% Elong	% RA
2000° F./12.0 ksi	M923	1176.5	34.4	42.4
[1093° C./83 MPa]	B924	960.4	37.4	42.9
2050° F./15.0 ksi	N923	143.7	20.7	36.5
[1121° C./103 MPa]	A924	135.8	26.3	38.2

Machining and Testing Source: Joliet Metallurgical Laboratory

[0052] A further heat (5V0459) of 100% Virgin (470 lbs) designated CMSX®-7 Mod B was melted in May 2011 in the CM V-5 Consarc VIM furnace using aim chemistry to CM KH Apr. 13, 2011 (CM CRMP #81-1703 Issue 1). The heat (5V0459) chemistry is shown in Table 6.

[0053] Two molds (#s 923 & 924) of SX NNS DL-10 test bars were cast to CMSX-4® casting parameters by Rolls-Royce Corporation (SCFO). DL-10 test bar yield at 22 fully acceptable out of a total 24 cast was excellent.

[0054] These DL-10 test bars were solutioned/homogenized+double aged heat treated at Cannon-Muskegon Corporation as follows—based on solutioning/homogenization studies on CMSX®-7 Mod B test bars.

Solutioning and Homogenization

[0055] 2 hrs/2360° F. (1293° C.)+2 hrs/2370° F. (1299° C.)

[0056] +2 hrs/2380° F. (1304° C.)+12 hrs/2390° F. (1310° C.) AC—ramping up at 1° F./min.

[0057] Double Age Heat Treatment

[0058] 4 hrs/2050° F. (1121° C.) AC

[0059] +20 hrs/1600° F. (871° C.) AC

[0060] Acceptable microstructure attainment is evident FIGS. **14** & **15**, almost complete γ' solutioning, remnant γ/γ' eutectic, no incipient melting and approximately 0.45 μm average cubic aligned γ', indicating appropriate γ/γ mismatch and γ/γ' inter-facial chemistry, following the 4 hr/2050° F. (1121° C.) high temperature age.

[0061] The creep-rupture properties of CMSX®-7 Mod B are very similar to that of CMSX®-7, with no apparent advantage (Table 7).

[0062] Post-test microstructures from a longer term, high temperature stress-rupture test [2000° F./12 ksi (1093° C./83 MPa)/1176.5 hours] are shown (FIGS. **19A**-**19C**) to exhibit good phase stability, with negligible TCP phase ("needles") apparent, combined with good stress-rupture life and rupture ductility (34% elongation (4D)) and 42% RA (FIGS. **19A**-**20C**).

[0063] The embodiments disclosed herein are non-limiting examples that are provided to illustrate and facilitate a better understanding, the scope of the invention being defined by the appending claims as properly construed under the patent laws, including the doctrine of equivalents.

What is claimed is:

1. A nickel-base superalloy for single crystal casting comprising:

5.60% to 5.85% aluminum by weight;

9.4% to 9.9% cobalt by weight;

5.0% to 6.0% chromium by weight;
0.08% to 0.35% hafnium by weight;
0.50% to 0.70% molybdenum by weight;
8.0% to 9.0% tantalum by weight;
0.60% to 0.90% titanium by weight;
8.5% to 9.8% tungsten by weight; and
the balance comprising nickel and minor amounts of incidental elements, the total amount of incidental elements being about 1% or less by weight.

2. A nickel-base superalloy for single crystal casting according to claim **1**, in which the incidental elements are controlled to maximums of 100 ppm carbon, 0.04% silicon, 0.01% manganese, 3 ppm sulfur, 30 ppm phosphorous, 30 ppm boron, 0.1% niobium, 150 ppm zirconium, 0.15% rhenium, 0.01% copper, 0.15% iron, 0.1% vanadium, 0.1% ruthenium, 0.15% platinum, 0.15% palladium, 200 ppm magnesium, 5 ppm nitrogen, and 5 ppm oxygen, each of any other incidental elements being present as a trace element at a maximum of about 25 ppm.

3. A nickel-base superalloy for single crystal casting according to claim **2**, in which the trace elements are controlled to maximums of 2 ppm silver, 0.2 ppm bismuth, 10 ppm gallium, 25 ppm calcium, 1 ppm lead, 0.5 ppm selenium, 0.2 ppm tellurium, 0.2 ppm thallium, 10 ppm tin, 2 ppm antimony, 2 ppm arsenic, 5 ppm zinc, 2 ppm mercury, 2 ppm cadmium, 2 ppm germanium, 2 ppm gold, 2 ppm indium, 20 ppm sodium, 10 ppm potassium, 10 ppm barium, 30 ppm phosphorous, 2 ppm uranium, and 2 ppm thorium.

4. A nickel-base superalloy for single crystal casting according to claim **1**, containing a maximum amount of sulfur of 0.5 ppm, and further comprising an amount of lanthanum and yttrium that is targeted to achieve a total lanthanum and yttrium content that is from about 5 ppm to 80 ppm in a single crystal casting.

5. A nickel-base superalloy for single crystal casting according to claim **1**, containing from 0.02% to 0.05% carbon by weight, and from 40 ppm to 100 ppm boron.

6. A nickel-base superalloy for single crystal casting according to claim **1**, having a density about 8.8 gms/cc (kg/dm^3).

7. A single crystal component cast from an alloy according to claim **1**.

8. A single crystal component according to claim **7** that is a gas turbine component.

9. A single crystal component according to claim **7** that is a blade, a vane, or a seal segment for a gas turbine.

* * * * *