ENHANCED RUPTURE PROPERTIES

IN ADVANCED SINGLE CRYSTAL ALLOYS

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Summary

The rupture lives of two single crystal alloys, CMSX-2 and CMSX-4G, were improved by extended thermal processing. The chemistries of the alloys were similar except for an addition of rhenium for high temperature stability in CMSX-4G. Two high temperature aging cycles were given to each alloy which resulted in γ' platelet formation and varying degrees of γ' coarsening. The effect of γ' coarsening on the rupture and tensile properties was investigated. The results for each alloy were compared to the ONERA aging cycle which produced a fine cuboidal γ' morphology in both alloys. It was found that overaging the γ' in CMSX-2 occurred more readily than in CMSX-4G.

Additionally, for CMSX-2, crystallographic orientations versus tensile and rupture properties from each aging cycle were evaluated. Regardless of the aging cycle, the [111] crystallographic orientation had the best rupture properties and the [001] orientation had the best tensile properties. Mechanical property testing in both portions of the study showed that extended thermal cycles resulted in increased rupture lives due to γ' platelet formation and coarsening with only minor decreases in tensile strength.

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Introduction

Advanced limited life gas turbine engines require high strength and rupture resistant turbine blades. Previous work in the area of single crystal superalloys has shown a large number of variables contributing to tensile and rupture behavior. (1,3,8,9) The most predominant variables were heat treatment, crystallographic orientation, and chemistry. The effect of high temperature/extended aging cycles and chemistry were evaluated to determine interactive effects on tensile and rupture properties in Cannon-Muskegon alloys CMSX-2 and CMSX-4G. High stress levels for the rupture tests were selected to produce the relatively short rupture lives, that are typical for limited life engines.

The two aging cycles investigated were based on previous work conducted at Williams International in developing an activated diffusion bonded multiple alloy turbine rotor with single crystal airfoils. These cycles were compared against the typical ONERA heat treatment to provide a common reference point. In addition to the study of aging cycles and chemistry modifications on single crystal properties, the effect of aging cycles on the mechanical properties of various crystallographic orientations was also evaluated for CMSX-2.

Experimental Procedure

Alloy Selection

CMSX-2 was chosen for evaluation since it was a well characterized single crystal alloy,that had been successfully used in other studies. CMSX-4G, a derivative of CMSX-2 was included due to reports of its increased creep rupture properties. The main difference in the chemistries of CMSX-2 and CMSX-4G was the addition of approximately 3 percent rhenium (Re). A small amount of hafnium (Hf) and additional cobalt (Co) was also added to the CMSX-4G alloy. The Re was added to reduce the coarsening rate by decreasing the diffusion kinetics at the γ/γ' interface, which results in increased high temperature microstructural stability. (10) Table I lists the chemistries of the two alloys.

Table I. Alloy Chemistries.

Alloy	Re	Hf	Al	Ti	Cr	W	Co	Mo	Nb+Ta	Ni
CMSX-2	0	0	5.66	1.02	7.9	7.9	4.7	0.6	6.05	Bal.
CMSX-4G	2.93	0.10	5.45	0.98	6.22	6.53	9.54	0.64	6.52	Bal.

Material Procurement

Earlier studies have shown that rupture properties vary with crystallographic orientation, (1,9) therefore the CMSX-2 evaluation included four major crystallographic orientations ([001], [011], [111], and [112]). The CMSX-4G portion of the study included only the [111] orientation, since the [111] had the best rupture properties behavior in the CMSX-2 study.

The CMSX-2 and CMSX-4G single crystal test material was produced by Howmet using the seeded Bridgeman technique. Different casting solidification rates were required to produce the different orientations needed for each alloy. Since the test material exhibited only minor differences in either the primary or secondary dendrite spacings, casting effects were considered negligible, which allowed a reasonable basis for comparing all the test material.

To avoid recrystallization, the CMSX-2 and CMSX-4G single crystal slabs and bars were solutioned immediately after casting. The solutioning cycles were different, due to the chemistry variations and different γ' solvus temperatures. A minimum of 99.7% of the γ/γ' eutectic was put into solution for both alloys.

The test material was Laue X-ray inspected. All of the tested specimens were within 10 degrees of the desired crystallographic orientation.

Material Test Plan

Two high temperature aging cycles were developed as part of an activated diffusion bonding study to produce multiple alloy turbine rotors. The effects of the rotor bond cycles on the rupture lives and tensile properties of the CMSX-2 and CMSX-4G were investigated to determine maximum rotor capabilities. These two cycles were compared to the standard ONERA aging cycle. The complete thermal processing sequences were as follows:

a. Solution Treatment
b. HIP: 1135°C/207 MPa/3 hrs.
c. Age

The aging cycles compared in this study were:

- o ONERA Heat Treatment (3) - 1050°C/16 hrs/furnace cool plus 850°C/48 hrs/furnace cool.
- o Cycle #1 - 1165°C/6 hrs/furnace cool plus 760°C/16 hrs/furnace cool
- o Cycle #2 - 1165°C/53 hrs/furnace cool plus 760°C/16 hrs/furnace cool.

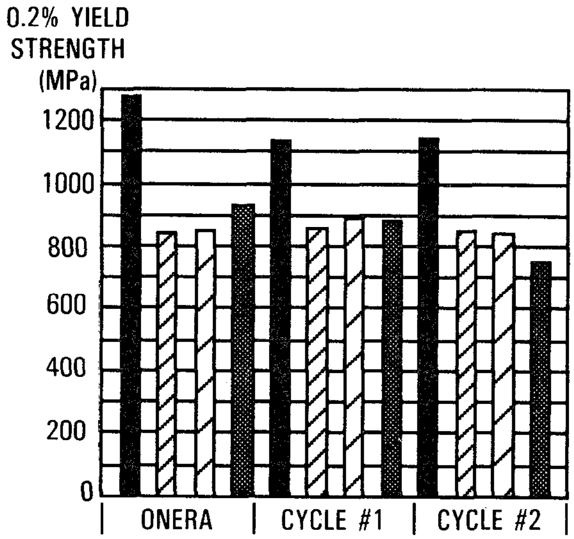
Most of the material was HIP'ed after solutioning because the activated diffusion bonding cycles included HIP'ing as part of the bonding operation. However, the material given the ONERA cycle was HIP'ed prior to solutioning per its standard processing cycle.

Results/Discussion

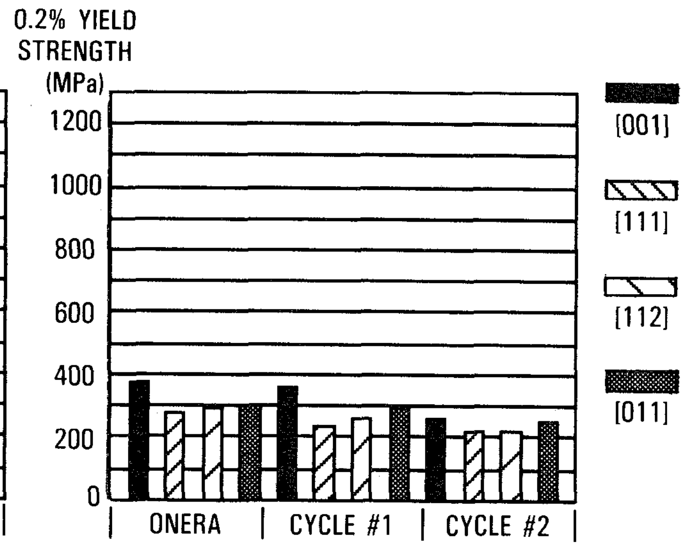
Aging Treatment and Orientation Effects on CMSX-2 Mechanical Properties

After the aging treatment, testing was conducted on the specimens in the [001], [011], [111], and [112] crystallographic orientations. The [001] orientation exhibited the highest tensile strength in all aged conditions and test temperatures. Previous work by other investigators confirm these findings. (9) The results of the CMSX-2 tensile tests are shown in Figure 1. For each crystallographic orientation, there was a reduction in tensile strength from cycle #1 to cycle #2, due to overaging caused by the longer aging cycle.

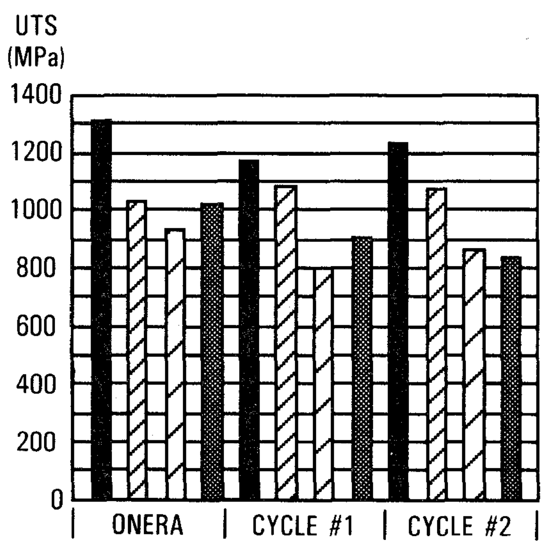
Rupture testing on CMSX-2 showed that the [111] orientation had the best properties. The rupture results are presented in Table II. The data shows that cycle #1 produced the best rupture properties, cycle #2 had slightly lower rupture properties, and the ONERA cycle had the shortest rupture lives.



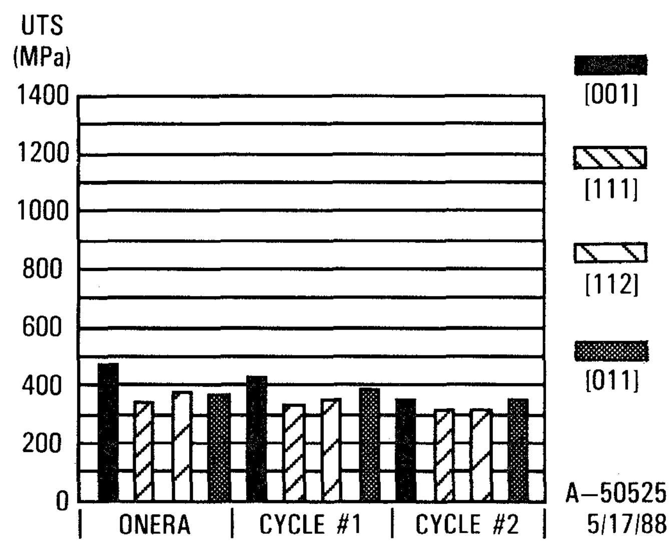
(a.) 0.2% Yield Strength (MPa) vs. Crystallographic Orientation and Aging Cycle for CMSX-2 at 760°C.



(b.) 0.2% Yield Strength (MPa) vs. Crystallographic Orientation and Aging Cycle for CMSX-2 at 1095°C.



(c.) Ultimate Tensile Strength (MPa) vs. Crystallographic Orientation and Aging Cycle for CMSX-2 at 760°C.



(b.) Ultimate Tensile Strength (MPa) vs. Crystallographic Orientation and Aging Cycle for CMSX-2 at 1095°C.

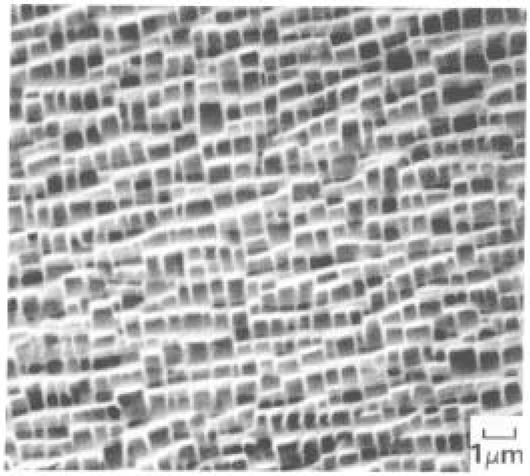
Figure 1. Tensile and Yield Strength vs. Crystallographic Orientation and Heat Treatment for CMSX-2.

Table II. Rupture lives in hours, for all of the tested orientations of CMSX-2 at 927 and 1095 degrees C.

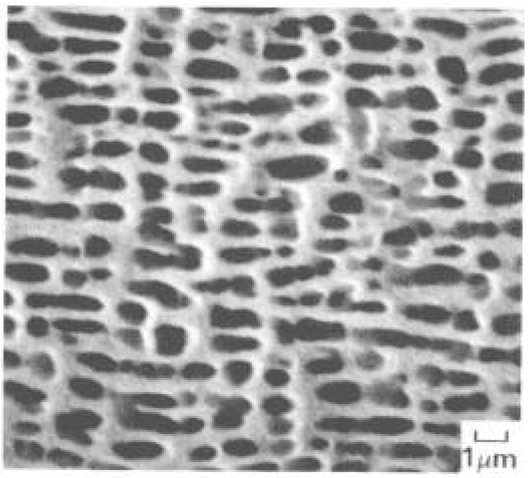
Orientation	Heat Treatment	Temp. (°C)	Stress (MPa)	Rupture Time (Hrs)
[001]	ONERA	927	345	64.3
[001]	Cycle #1	927	345	134.5
[001]	Cycle #2	927	345	72.1
[011]	ONERA	927	345	66.2
[011]	Cycle #1	927	345	121.7
[011]	Cycle #2	927	345	65.0
[111]	ONERA	927	345	98.4
[111]	Cycle #1	927	345	153.1
[111]	Cycle #2	927	345	114.3
[112]	ONERA	927	345	68.5
[112]	Cycle #1	927	345	110.2
[112]	Cycle #2	927	345	91.7
[001]	ONERA	1095	117	56.0
[001]	Cycle #1	1095	117	293.1
[001]	Cycle #2	1095	117	81.1
[011]	ONERA	1095	117	54.8
[011]	Cycle #1	1095	117	189.3
[011]	Cycle #2	1095	117	88.9
[111]	ONERA	1095	117	63.7
[111]	Cycle #1	1095	117	328.2
[111]	Cycle #2	1095	117	117.6
[112]	ONERA	1095	117	81.7
[112]	Cycle #1	1095	117	270.7
[112]	Cycle #2	1095	117	61.2

Figures 2a, b, and c show the γ' morphology of CMSX-2 in all three conditions. The ONERA cycle produced a fine cuboidal γ', while cycles #1 and #2 produced platelet γ' morphologies. The higher temperature and shorter time of Cycle #1 produced a fine platelet type γ' morphology that had the same width as the ONERA cycle's cuboidal γ'. The extended aging time in Cycle #2 coarsened the platelets in both length and width. Similar results on platelet coarsening were shown by Nathal. (8) The actual γ' dimensions are shown in Table III.

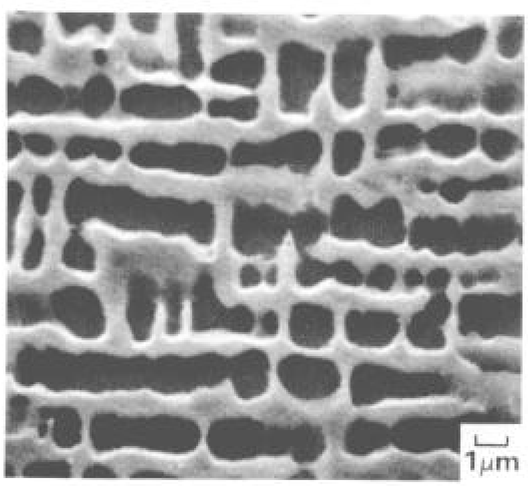
The platelet type γ' morphologies were more effective at impeding dislocation motion, because the dislocations must shear the γ' rather than circumventing as is possible with cuboidal structures. This resulted in increased rupture lives.[1] The finer γ' platelet morphology characteristic of Cycle #1 had better rupture properties than Cycle #2's coarse γ' platelet, since it had a higher γ/γ' surface area which provided more barriers to dislocation motion. It was concluded that cycle #2 coarsened and overaged the γ', which resulted in the shorter rupture lives.



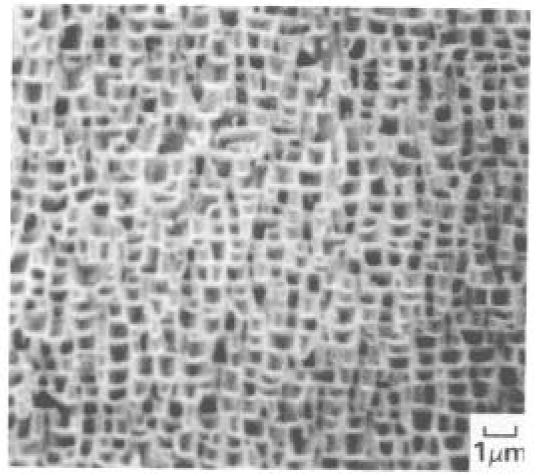
(a.) CMSX-2 with the ONERA Aging cycle. 3800X.



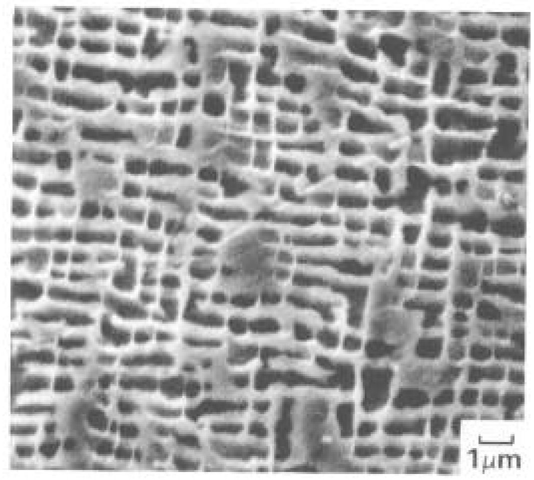
(b.) CMSX-2 with Aging Cycle #1. 3800X.



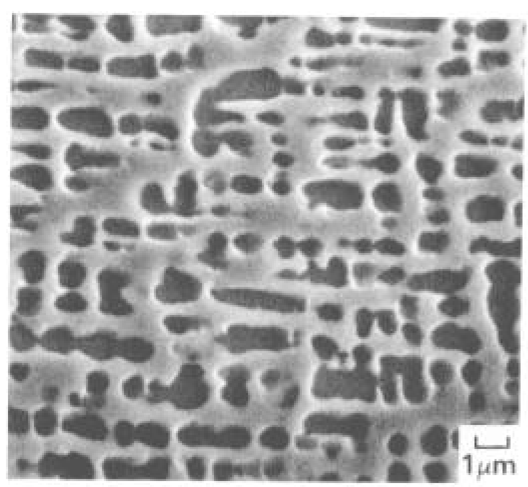
(c.) CMSX-2 with Aging Cycle #2. 3800X.



(d.) CMSX-4G with the ONERA Aging cycle. 3800X.



(e.) CMSX-4G with Aging Cycle #1. 3800X.



(f.) CMSX-4G with Aging Cycle #2. 3800X.

Figure 2. Photomicrographs of γ' Morphology as a Function of Aging Cycle and Alloy. γ' elongated in the [001] direction.

Aging Cycle Effects on CMSX-4G Compared to CMSX-2

The aging cycle response of CMSX-4G in the [111] orientation was compared to CMSX-2 by observing the growth and morphology change in the γ' and by measuring the resultant mechanical properties. The two cycles produced dramatic differences on the γ' morphology, which resulted in changes in tensile and rupture properties. The γ' morphologies of the two alloys that form after each of the aging cycles are shown in Figure 2. Table III lists the approximate γ' size and morphology for CMSX-2 and CMSX-4G.

The ONERA aging cycle produced a fine cuboidal γ' morphology in CMSX-4G as observed in CMSX-2. These microstructures served as a baseline for comparison of structures produced from the other cycles for both alloys.

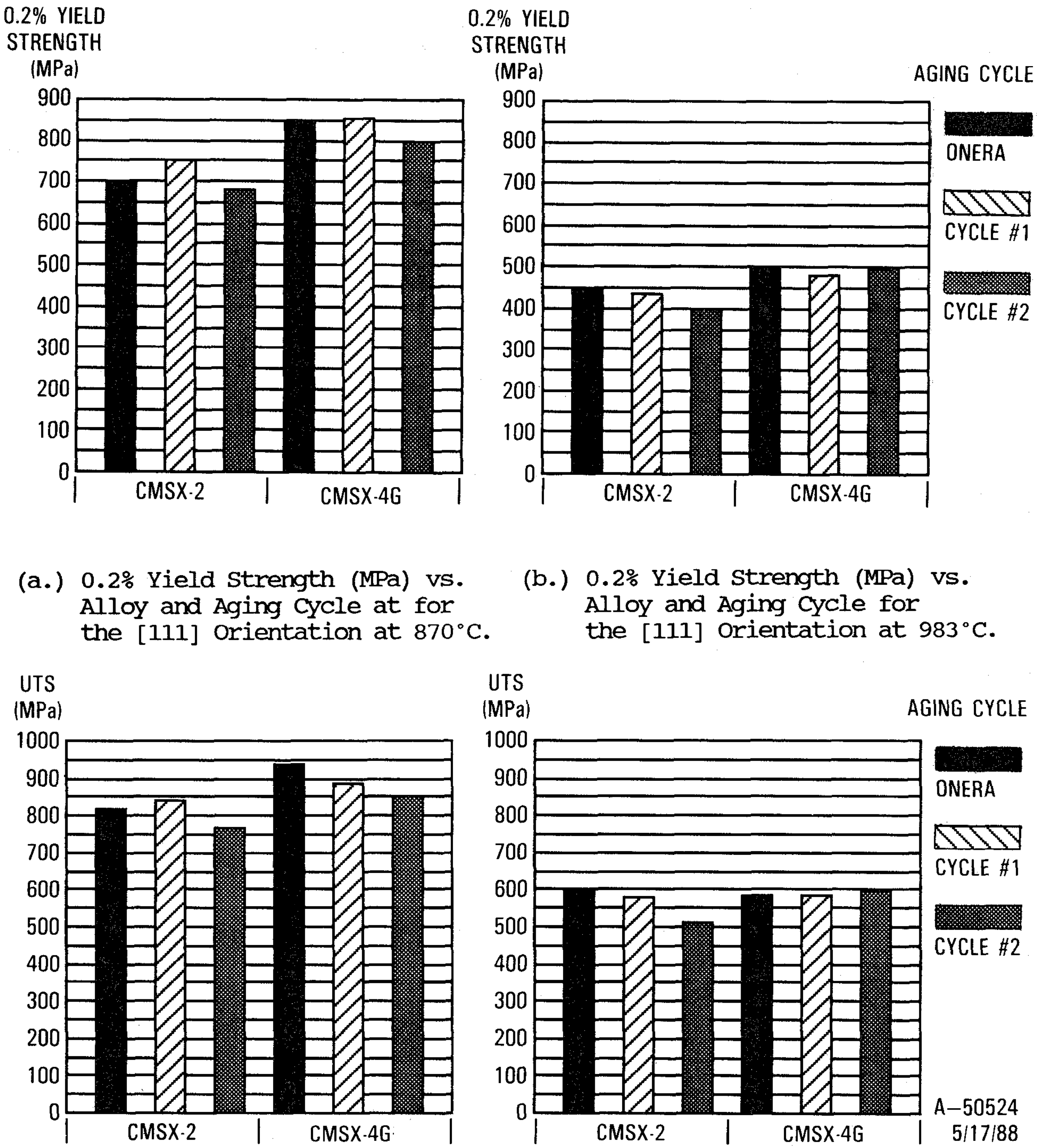
The CMSX-4G photomicrographs show that the Re addition tended to retard both the platelet formation and subsequent coarsening. As was shown in CMSX-2, Cycle #1's higher temperature/short time aging cycle promoted γ' platelet formation in CMSX-4G. However, the platelet formation appeared to be retarded due to the Re addition. Cycle #2's increased aging time promoted longitudinal growth of the γ' platelet rather than thickening of the platelet as seen in CMSX-2. It was observed that for all the aging cycles, the CMSX-4G containing Re had a finer γ' platelet structure. The Re addition has apparently inhibited the coarsening of the γ' platelets, that occurred in CMSX-2.

Table III. Approximate γ' size and morphology for each alloy and aging cycle.

	ONERA	Cycle #1	Cycle #2
CMSX-2			
width	0.5um	0.5um	1.0um
length	0.5um	1.5um	4.0um
l/w	1.0	3.0	4.0
CMSX-4G			
width	0.5um	0.5um	0.75um
length	0.5um	1.0um	2.5um
l/w	1.0	2.0	3.3

The longest rupture lives for CMSX-4G were achieved with aging cycle #2, indicating that CMSX-4G has more stability and can be subjected to prolonged thermal treatments without overaging which was not the case for CMSX-2. Table IV shows the rupture lives, in hours, for both alloys in all aged conditions. CMSX-4G has longer rupture times than CMSX-2 for either high temperature aging cycle. The CMSX-4G rupture life is nearly doubled at 927°C for cycle #2, compared to the ONERA aging cycle.

The tensile strength of CMSX-4G and CMSX-2 resulting from all of the aging cycles is shown in Figure 3. CMSX-4G had higher tensile strength than CMSX-2 in any of the aging cycles. The superior tensile strength of CMSX-4G was inherent to the alloy chemistry, since the tensile properties were better than CMSX-2 regardless of the aging cycle.



(a.) 0.2% Yield Strength (MPa) vs. Alloy and Aging Cycle at for the [111] Orientation at 870°C.

(b.) 0.2% Yield Strength (MPa) vs. Alloy and Aging Cycle for the [111] Orientation at 983°C.

(c.) Ultimate Tensile Strength (MPa) vs. Alloy and Aging Cycle for the [111] Orientation at 870°C.

(d.) Ultimate Tensile Strength (MPa) vs. Alloy and Aging Cycle for the [111] Orientation at 983°C.

Figure 3. Tensile Strengths of CMSX-4G and CMSX-2 vs. Aging Cycle.

Table IV. Rupture Lives as a Function of Aging Cycle and Alloy.

Heat Treatment	Temperature °C	Stress (MPa)	Rupture Time (Hrs.) CMSX-4G	Rupture Time (Hrs.) CMSX-2
ONERA	927	483	15.0	11.6
CYCLE #1	927	483	18.5	17.0
CYCLE #2	927	483	29.0	15.6
ONERA	1095	117	165.7	63.7
Cycle #1	1095	117	208.5	328.2
Cycle #2	1095	117	427.3	117.6
ONERA	1150	83	*	51.7
Cycle #1	1150	83	*	135.3
Cycle #2	1150	83	*	72.5

Conclusions

1. The morphology of the γ' in single crystal CMSX-2 and CMSX-4G alloys was modified by thermal processing. An aging temperature of approximately 1050°C produced fine cuboidal γ'. Increasing the aging temperature to 1165°C caused the γ' to have a platelet morphology.

2. The aging cycles had a significant effect on the mechanical properties of single crystal CMSX-2 and CMSX-4G alloys due to the resultant γ' morphology and coarsening rate. Time at temperature and composition dictated the rate of γ' platelet formation and subsequent coarsening.

3. For CMSX-2, the [111] orientation had better rupture properties than the [001], [011], or [112], regardless of aging cycle. The [001] orientation had better tensile properties than the [011], [111], or [112], regardless of aging cycles in CMSX-2.

4. For CMSX-2, the fine γ' platelet morphology produced in cycle #1 optimized rupture properties. Overaging associated with cycle #2 coarsened the platelet γ', decreasing rupture properties. However, both of these aging cycles resulted in increased rupture properties compared to the ONERA cycle.

5. For CMSX-4G, the rupture properties were improved with cycle #2. CMSX-4G exhibited platelet lengthening with the longer thermal cycle resulting in increased rupture properties.

6. The CMSX-4G chemistry modifications resulted in better rupture and tensile strengths than found in CMSX-2. The Re additions in CMSX-4G resulted in a much more stable γ' structure, which allowed longer aging cycles without coarsening and overaging the γ' platelets.

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