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PRACTICAL EXPERIENCE WITH FULL SOLUTION REJUVENATION OF SINGLE CRYSTAL GAS TURBINE BLADES

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Abstract

Thermal degradation of precipitation-hardened nickel based superalloys has been demonstrated to be reversible through full solution rejuvenation heat treatment processing. The specific concern with full solution rejuvenation heat treatment of single crystal alloys is the formation of recrystallized grains on surfaces with residual stress. In a previous study it was demonstrated that the effects of recrystallization can be mitigated through post heat treatment processing, provided the recrystallization is limited to the surfaces of the blade root. In order to further assess the feasibility of single crystal rejuvenation, service run, life expired blades were processed fully through the repair process, including full solution rejuvenation. The effectiveness of the repair was evaluated using non-destructive testing, optical and scanning electron microscopy and stress rupture testing. It was demonstrated that full solution rejuvenation repair of single crystal blades is feasible. The propensity for recrystallization depended on prior plastic deformation from service, manufacture and/or repair processing.

1 Introduction

Improvements in turbine blade technology have resulted in significant increases in the inlet temperatures of gas turbines. These improvements have included advanced internal cooling, thermal barrier coatings and single crystal alloys [1]. With the improved capability has come increased cost of new components. A single crystal blade can cost 2 to 3 times that of a conventionally cast blade of similar size and complexity. The increased cost of single crystal parts provides operators further motivation to maximize the service life of the components. In many cases it has been found that the OEM life of industrial single crystal gas turbine blades has been limited to two service intervals of approximately 18,000 to 25,000 hours each, with one repair between the intervals consisting primarily of removal and replacement of the coating. These OEM limits appear to be conservative based on the limited observed damage on destructively examined ‘life expired’ single crystal blades.

The significant cost of replacement components has resulted in the development of repair processes to extend the life of components. One such process is full solution rejuvenation heat treatment which restores the alloy microstructure and mechanical properties to the like-new condition.

Full solution (above the γ' solvus) rejuvenation heat treatments have been employed successfully since the 1970s to extend the life of turbine blades comprised of polycrystalline and directionally solidified nickel based superalloys [2]. The primary concern with full solution rejuvenation heat treatment of single crystal alloys is the formation of recrystallized grains on surfaces with residual stress, particularly given the lower levels of grain boundary strengthening alloying additions from single crystal alloys [3, 4]. Recrystallized and/or stray grains in single crystal alloys have been shown to result in reduced high temperature fatigue life and stress rupture strength [5-7]. Accordingly they are inspected for and are cause for rejection at original manufacture (this is one of the contributing factors for the higher prices of single crystal castings). An example of a service run single crystal alloy blade with a stray grain not found during manufacture in the airfoil to shroud radius that resulted in cracking is shown in **Figure 1**.

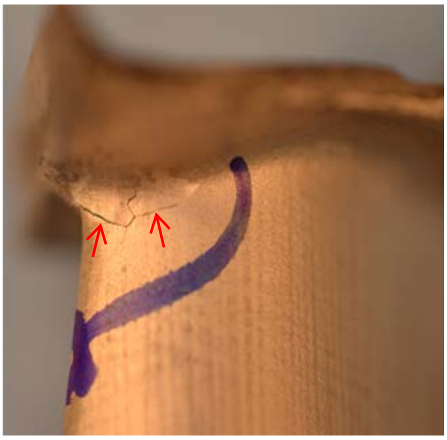

Figure 1: An example of a service run blade comprised of a single crystal alloy, exhibiting cracking along the grain boundary of stray grains in the airfoil to shroud radius (indicated by red arrows).

In a previous study, it was found that recrystallization did not result in a reduction in high cycle fatigue life of a second generation single crystal superalloy (René N5) tested at 650°C [8]. The findings indicate that full solution rejuvenation heat treatment of previously peened single crystal blades is feasible provided that recrystallization be limited to root surfaces which operate approximately at or below 650°C, since high cycle fatigue is considered the primary damage mechanism in this region rather than creep.

In order to further assess the feasibility of full solution rejuvenation heat treatment of single crystal turbine blades, a trial repair of life expired blades (per OEM life limit) comprised of CMSX-4 single crystal alloy was conducted. Based on the foregoing discussion, there are unique considerations that need to be applied to rejuvenation repair of single crystal blades. Specifically, it is necessary to ensure that during repair processing critical surfaces of the blades are not subject to plastic deformation which may result in subsequent recrystallization. Additionally, it is necessary to have an effective non-destructive inspection method to examine for recrystallization on critical surfaces after the heat treatments have been applied.

2 Scope of the Analysis

Six life expired Siemens SGT-100 HP turbine blades comprised of CMSX-4 single crystal alloy were used for demonstration repair and destructive analysis, **Figure 2**. The blades were reported to have operated for approximately 28,000 hours, following which they were repaired once and then operated for an additional approximately 12,000 hours (i.e. approximately 36,000 total service hours). At this point the blades were deemed to be life expired per the manufacturer's life limit for the component. The basis for the life limit (the life limiting damage mechanism) was unknown.

Figure 2: As received appearance of the blades used for repair demonstration (concave and convex side). Note that the blades had been 'notched' on the trailing edges identifying them as unserviceable.

One representative blade from the set was destructively examined in the service run, as received condition to establish a baseline for the metallurgical condition of the blades prior to repair processing. The remaining five blades were subject to repair which included: removal of the coating, dimensional and penetrant inspection, solution heat treatment (above the gamma prime solvus), ageing heat treatments and replacement of the external platinum aluminide coating. Destructive analysis of the blades in both the as received and post repair conditions included: scanning electron microscopy of the base alloy (gamma prime morphology), stress rupture testing of mini-flat sheet specimens taken from the airfoil, and microscopic examination of the internal and external surfaces. The destructively examined blades were sectioned according to the schematic shown in **Figure 3**.

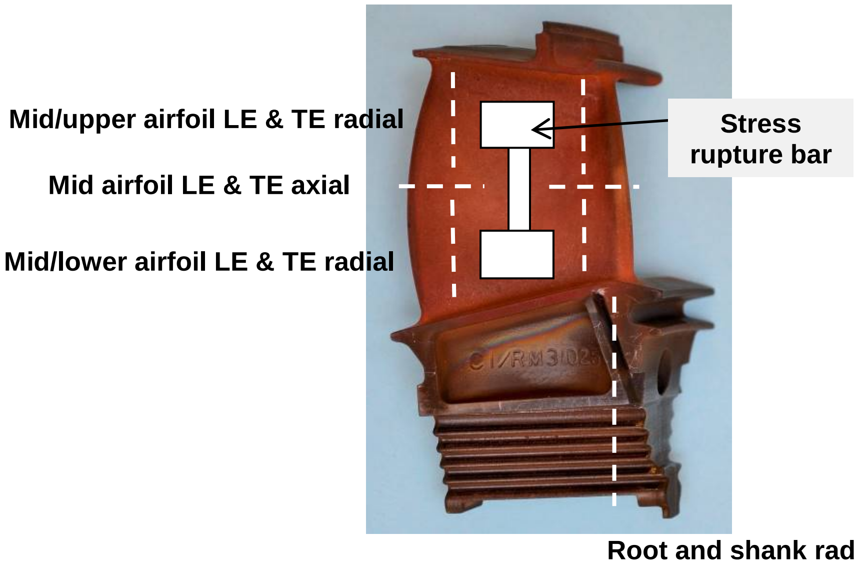

Figure 3: Sectioning plan for the destructively examined blades.

3 Post Service, As Received Condition Assessment

3.1 Surface Condition

The external airfoil surfaces were coated with a platinum aluminide coating, **Figure 4 left**. The coating was partially consumed, however, it had provided effective protection for the prior service interval as no damage to the underlying base alloy was observed.

The internal airfoil surfaces were uncoated, **Figure 4 right**. Minor base alloy oxidation was observed on the internal surfaces, penetrating <25µm (0.001 inches) deep.

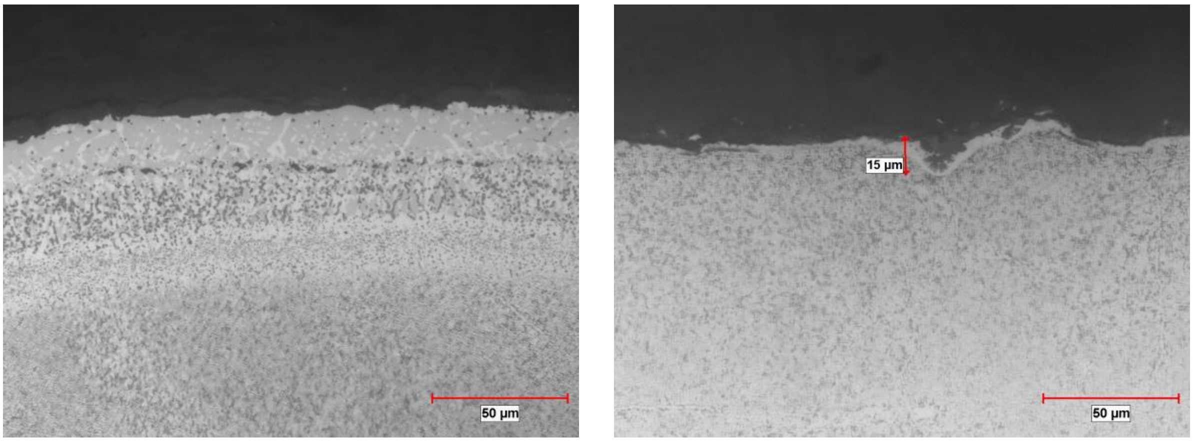

Figure 4: Micrographs of the post service, as received external (left) and internal (right) airfoil surface conditions.

An alloy denuded layer 20µm thick was observed on the surface of the root, **Figure 5**. The layer was considered likely to be a result of original manufacture and/or repair processing rather than service induced as no oxidation was evident on the surface. For example, it may have been due to a reaction with a processing material or atmosphere. No recrystallization was observed on the root surfaces.

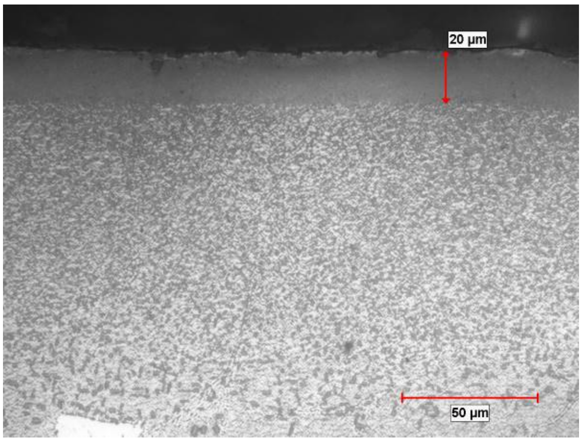

Figure 5: Micrograph of the post service, as received root surface condition.

3.2 Base Alloy Condition

The γ’ structure in the root is considered representative of the alloy’s pre-service condition, as the root operates at temperatures below which observable microstructural degradation occurs. The γ’ structure in the root was observed to be characteristic of fully heat treated CMSX-4 alloy, exhibiting a high density of cuboidal primary γ’ precipitates with fine secondary γ’ precipitates dispersed throughout, **Figure 6 left**. No appreciable aging (microstructural degradation) was observed at the examined airfoil locations in comparison to the root, **Figure 6 right**.

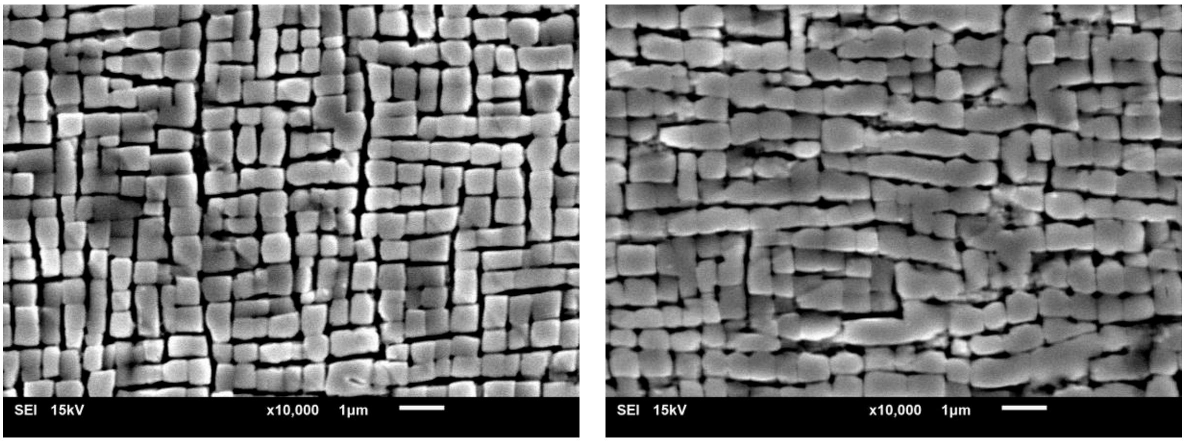

Figure 6: Micrographs of the post service, as received gamma prime morphology of the root (left) and mid to upper airfoil trailing edge (right).

3.3 Stress Rupture Testing

Stress rupture testing was performed in accordance with ASTM E139 on a mini-flat specimen taken from the mid chord of the pressure side airfoil with the gage section centered at the mid height of the airfoil. Testing was conducted at 997°C (1826°F) using an applied load of 250MPa (36,300 psi). The result is shown in **Table 1**.

Table 1 – Post Service, As Received Stress Rupture Test Result

Location	Life (hours)	Elongation (%)
Mid chord airfoil, pressure side	82.8	30.6

4 Rejuvenation Heat Treatment Repair Condition Assessment

4.1 Non-destructive Inspection

Following coating removal, the blades were inspected for surface exposed cracks or defects by fluorescent penetrant inspection (FPI). No indications were identified.

Following coating removal, 3 blades were also subject to dimensional inspection which included trailing edge thickness, ultrasonic wall thickness, root width, and seal height. All measurements met the acceptance criteria for continued service.

After removing the coating, 3 blades were scanned with a laser coordinate measuring machine (CMM). The same blades were re-scanned with the CMM following solution heat treatment, and a deviation analysis was produced which reveals any geometric change or distortion of the blade resulting from the heat treatment. No significant changes occurred as a result of the heat treatment, **Figure 7**.

Figure 7: Typical CMM deviation analysis of a blade showing no significant dimension change/distortion after solution heat treatment. Units: inches.

4.2 Surface Condition

After rejuvenation processing including full solution heat treatment (above γ' solvus), the blades were non-destructively inspected for recrystallized grains in critical areas by chemical etching. Four out of the five blades were found to exhibit recrystallized grains in critical areas to varying extents, an example of which is shown in **Figures 8 and 9**. Destructive examination verified that the depth of recrystallization in the case of at least one blade was beyond serviceable limits (not all recrystallized areas were destructively examined).

Based on this finding, an additional twelve life expired blades were submitted for further analysis – seven from the same blade set as the six originally tested blades and five from a different blade set. All blades were subject to repair which included coating removal and full solution heat treatment rejuvenation processing followed by macro etch inspection for recrystallized grains. All blades were found to initially exhibit some recrystallized grains in critical areas to varying extents. The blades were then put through a cycle of mechanically removing the grains and re-inspection until the recrystallized grains had been eliminated from all critical areas. Finally, eight blades were destructively examined (five from the group of seven, and three from the group of five) to verify the inspection results and assess the remaining wall thickness. All seven blades from the first group were found to be within repair limits and four out five of the blades from the second group were found to be within repair limits.

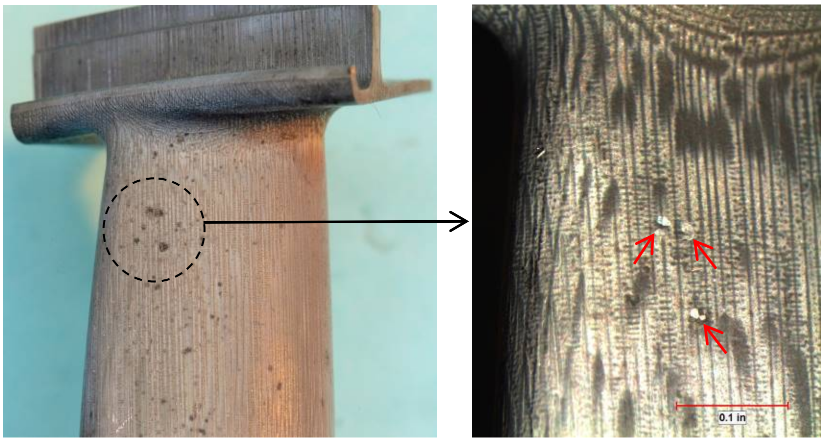

Figure 8: Example of recrystallized grains (indicated by red arrows) on the airfoil after rejuvenation heat treatment processing and chemical etching. The grains appeared to have nucleated from minor service related impacts on the convex leading edge.

Two of five initial trial repair blades were recoated with a platinum aluminide coating. Both coated and uncoated blades from the initial group of five blades were destructively examined post repair. Recrystallized grains were observed at the upper airfoil leading edge external surface penetrating up to 170µm (0.0067 inches) deep on the uncoated blades, **Figure 9**. On the coated samples, all surfaces were found to be fully coated. The coating met the specified requirements for the application.

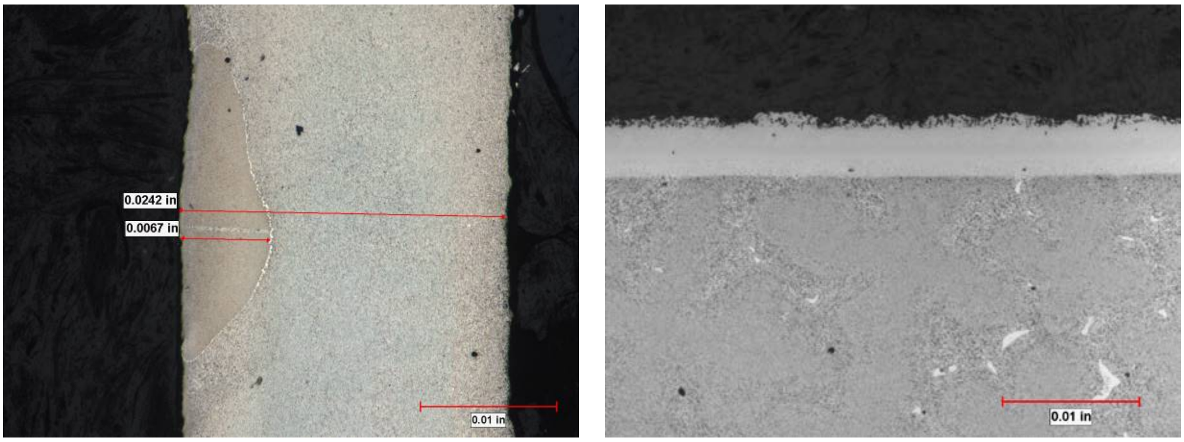

Figure 9: Micrographs of the external airfoil surface condition, post rejuvenation heat treatment. Recrystallized grains were observed in some cases (upper airfoil leading edge shown at left). On the coated samples, all surfaces were fully coated (right).

No recrystallization was observed on the internal airfoil surfaces of any of the examined sections.

A relatively uniform layer of fine recrystallized grains penetrating up to approximately 125µm (0.005 inches) deep was observed on the root serrations of each of the destructively examined blades, **Figure 10**. The recrystallized layer indicates that the root surfaces had likely been peened at original manufacture.

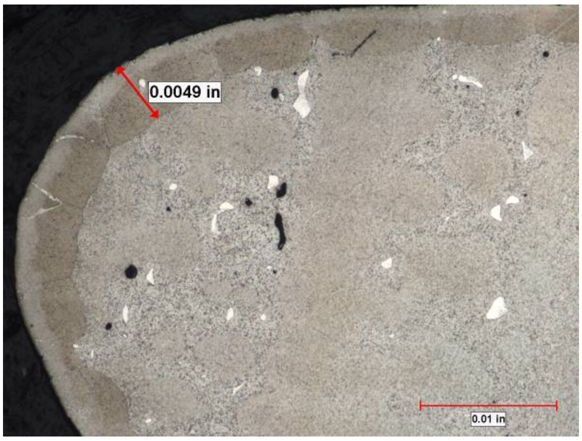

Figure 10: Micrograph of the typical post rejuvenation repair root surface condition exhibiting a layer of recrystallized grains on the surface.

4.3 Base Alloy Condition

Following full solution (above γ' solvus) and ageing heat treatments, the γ' structure in the root and airfoil was observed to be typical of fully heat treated CMSX-4 alloy, comparable to the as manufactured root microstructure (refer to Figure 6 left), **Figure 11**.

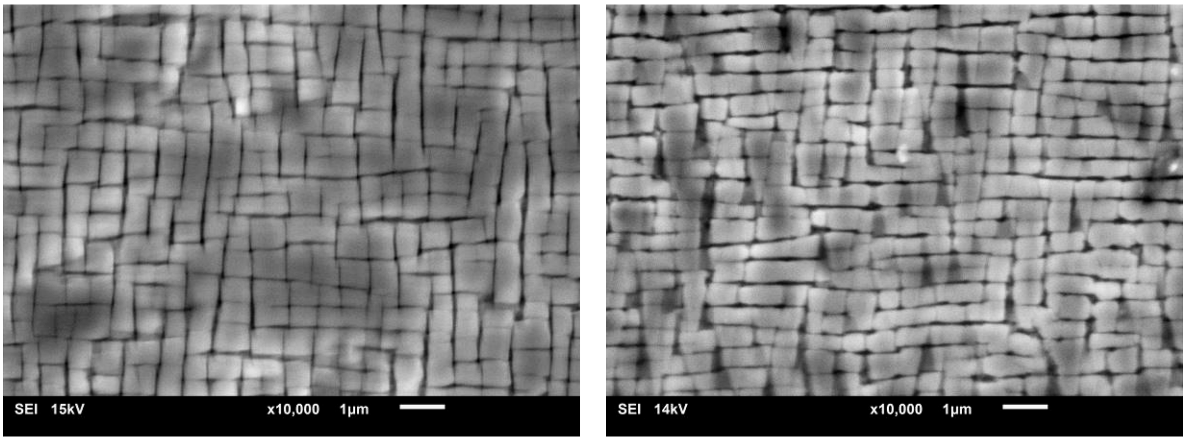

Figure 11: Micrographs of the post rejuvenation repair gamma prime morphology of the root (left) and mid to upper airfoil trailing edge (right).

4.4 Stress Rupture Testing

Following the full solution rejuvenation repair, stress rupture testing was performed in accordance with ASTM E139 on a mini-flat specimen taken from the mid chord of the pressure side airfoil of two blades with the gage section centered at the mid height of the airfoil. Testing was conducted at 997°C (1826°F) using an applied load of 250MPa (36,300 psi). The results are shown in **Table 2**.

Table 2 – Post Rejuvenation Repair Stress Rupture Test Results

Blade	Location	Life (hours)	Elongation (%)
1	Mid chord airfoil, pressure side	102.2	37.1
2	Mid chord airfoil, pressure side	96.9	28.0

The as received and post rejuvenation stress rupture results are shown on a Larson Miller plot in comparison with fully heat treated CMSX-4 stress rupture data from literature [9], **Figure 11**.

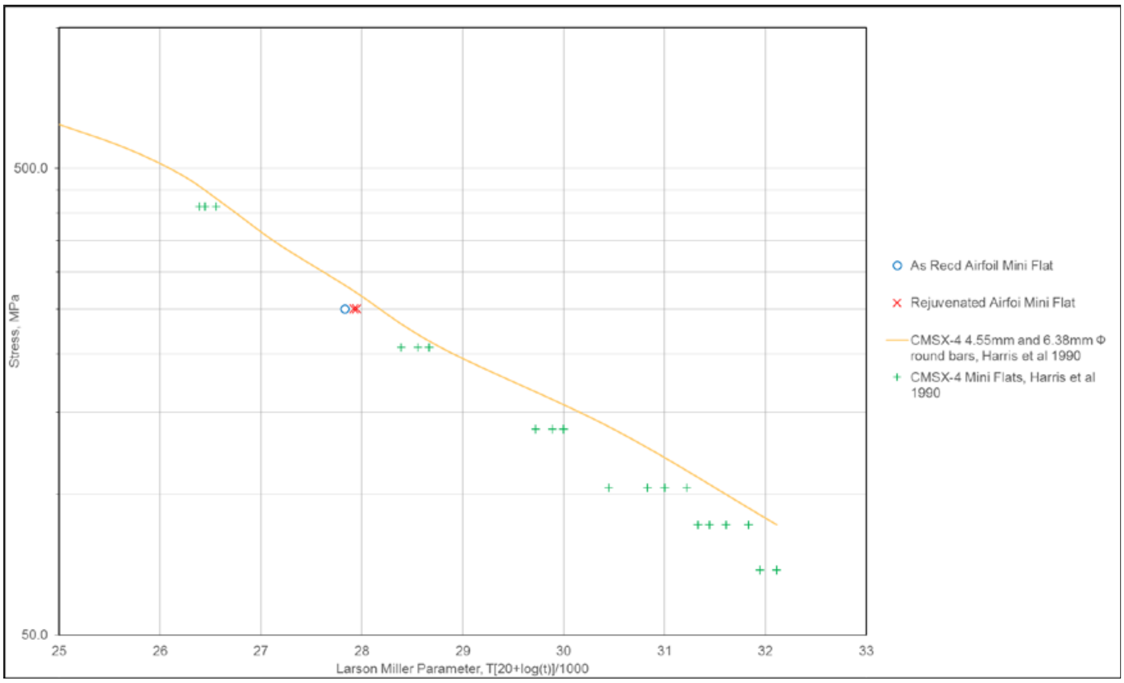

Figure 11: Larson Miller plot comparing the as received and rejuvenated stress rupture results with data from literature for fully heat treated CMSX-4 [9].

5 Discussion

Based on the destructive and non-destructive testing performed, the examined blades were found to be in a serviceable condition despite having reached the OEM life limit. In cases where the life limiting damage mechanism is unknown, it is prudent to apply full solution rejuvenation heat treatment in order to anneal any pre-crack damage accumulation that may be undetectable by conventional testing. Additionally, there may be degradation of mechanical properties in locations of the blade in which it is not possible to perform mechanical testing. For example, in a shroud radius or thin trailing edge wall.

The post service, as received microstructure and stress rupture properties in the main body of the airfoil were not found to be appreciably degraded. However, the trial repair demonstrated that the heat treatment schedule applied resulted in a microstructure comparable to the as manufactured microstructure, with stress rupture properties equivalent to those published in the literature for fully heat treated CMSX-4 alloy.

Just as new single crystal castings are subjected to post casting grain inspections, full solution rejuvenation repaired blades also need to be inspected for recrystallization, with neither process expected to yield 100%. Of the examined blades, at least two out of seventeen blades were found to have recrystallized grains in critical areas beyond repair limits. However, it was demonstrated that a significant proportion of the tested blades were recovered within repair limits through a cycle of mechanically removing the grains, re-inspection and subsequent non-destructive wall thickness measurements.

The full solution heat treatment also resulted in a recrystallized layer on the root surfaces of the repaired blades. This indicates that the root surfaces had been peened during original manufacture and/or prior repair. The depth of recrystallization on the roots was comparable to that of a previous study which found that recrystallization of root surfaces of single crystal blades was an acceptable condition for continued operation with post heat treatment processing [8].

6 Conclusions

It was demonstrated that full solution rejuvenation repair of single crystal blades is feasible. The post repair alloy microstructure and stress rupture properties were equivalent to the as-new condition. It was found that the propensity for recrystallization depended on prior plastic deformation from manufacture, service, and/or repair processing. An effective non-destructive inspection technique for recrystallized grains is necessary when performing this type of repair, just as it is necessary to perform grain inspection on new single crystal castings. While some fallout is likely to occur due to recrystallization in critical areas beyond reapair limits, the trial demonstrated that high repair yields can be achieved for this type of repair.

Acknowledgements

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