Mechanical Properties Evolution of γ'/γ'' Nickel-Base Superalloys During Long-Term Thermal Over-Aging

A. AGNOLI, C. LE GALL, J. THEBAULT, E. MARIN, and J. CORMIER

The long-term stability of Inconel 718 and Waspaloy forgings in the 600 °C to 850 °C temperature range and up to 10,000 hours was studied by means of mechanical tests and microstructural analyses. Hardness and tensile properties were found to decrease with increasing over-aging time and temperature. The comparative analysis of tensile results of both alloys indicates that they exhibit an equivalent stability over time if the over-aging temperature of Waspaloy is increased by 50 °C to 100 °C compared to Inconel 718. No detrimental intermetallic precipitation at grain boundaries has been detected in both alloys. Microstructure characterizations performed by scanning electron microscopy indicate that the higher stability of Waspaloy can be attributed to the slower kinetics of coarsening and dissolution of γ' precipitates with respect to γ'' precipitates that account for the majority of hardening particles in Inconel 718. Additionally, fatigue results indicate that in both alloys over-aging promotes surface crack initiation, thus leading to shorter fatigue life.

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I. INTRODUCTION

NICKEL-BASE superalloys are commonly used for the manufacturing of turbine engine rotating components such as disks or seal rings because of their excellent mechanical properties at high temperature.[1,2] Their capability to retain strength at high temperature derives from the size and distribution of fine precipitates (γ' or γ'') that directly affect the mechanical properties.[3–7] Hence, mechanical properties of Ni-base superalloys components can evolve if in-service conditions induce a modification of the size or distribution of precipitates due to thermal over-aging.[7–9] A decrease in tensile and creep resistance is generally observed in most γ' or γ'-γ'' strengthened Ni-base superalloys due to either the growth of strengthening precipitates[7,9–13] or the precipitation of intermetallic topologically close packed (TCP) phases,[13–16] or both. An exception to these general trends can be observed in Alloy 625. In this alloy, which is almost always used in a solid-solution state, γ'' and $Ni_2(Cr,Mo)$ intermetallic precipitations are likely to occur in the 500 °C to 700 °C temperature range, hence improving both tensile, creep, and LCF properties.[17–22]

Among nickel-base superalloys, Inconel 718 and Waspaloy have been widely used for manufacturing turbine disks and rings since their first development in the 50s.[2,23–26] As a consequence, forging processes and mechanical properties of these superalloys with optimized microstructures are well known.[10,27–31] However, last generation engines are more and more demanding, especially in terms of operating temperatures. In fact, higher temperatures in turbine disks or seal rings are required in order to improve the engine performance. Traditionally used alloys such as Alloy 718 and Waspaloy are hence pushed to their limits in terms of microstructure stability. Microstructural evolution such as the growth of strengthening precipitates and secondary phases is likely to occur,[10] then affecting tensile and fatigue over time, leading to a shorter life and a premature replacement of engine components with respect to the initial design. In this regard, the impact of thermal over-aging on the mechanical properties must be addressed in order to assess if current generation superalloys can still be used in future engines or if they must be replaced by new ones having a better high-temperature stability. Indeed, from an industrial point of view, the possibility to expand the application range of well-known superalloys is an advantageous solution compared to the risks and costs of developing new alloys.

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Several studies have already investigated the impact of over-aging of Inconel 718 on its microstructure and mechanical properties.[6,10,32,33] However, most of the studies have been focused on short-term thermal over-aging (duration lower than 1000 hours) and precipitates evolution. Very few studies have addressed the long-term stability of Inconel 718 (durations longer than 1000 hours) and the impact on mechanical properties other than hardness, such as tensile, fatigue and creep resistance,[8] or crack propagation rate. The situation is similar regarding Waspaloy with few previous studies addressing the long-term stability of this alloy,[34] and the consequences on mechanical properties.[11,12]

Within this context, the main aim of this work is to characterize the impact of thermal over-aging (in the temperature and duration ranges 600 to 850 °C and 300 to 10,000 hours, respectively) on the mechanical properties (hardness, tensile properties, low cycle fatigue (LCF)) of Inconel 718 and Waspaloy forgings. Mechanical property changes will be discussed taking into account the precipitates evolution during over-aging.

II. EXPERIMENTAL PROCEDURES

All specimens were machined from turbine engine forgings of Safran Aircraft Engines. Inconel 718 forgings were direct-aged (8 hours at 720 °C followed by controlled cooling down to 620 °C at 50 °C h^{-1} and by 8 hours at 620 °C, air cooling). After heat treatment, the grain size was mostly unimodal (10 to 12 ASTM) and the area fraction of the δ phase (Ni_3Nb) was about 4 pct. Waspaloy forgings were annealed (4 hours at 1010 to 1035 °C, oil cooling) and aged (4 hours at 850 °C followed by 16 hours 760 °C, air cooling). After heat treatment, the grain size was mostly bimodal with a finer (7 to 9 ASTM) and a coarser (3 to 5 ASTM) population. Average chemical compositions of Inconel 718 and Waspaloy are provided in Table I. With such a chemical composition, alloy 718 is primarily strengthened by γ'' particles (Ni_3Nb type particles of $D0_{22}$ structure) and, to a lower degree, by γ' precipitates (Ni_3Al type particles of $L1_2$ structure).[6,10,35,36] Depending on the forging and thermal exposure conditions, δ particles (Ni_3Nb type particles of $D0_a$ structure) can also be present with almost no strengthening. Waspaloy is mainly strengthened by a unimodal or multi-modal distribution of γ' precipitates (Ni_3Al type particles of $L1_2$ structure) depending on aging heat treatments.[11,37]

Isothermal over-aging treatments were performed on blanks (machined from forgings) that were subsequently machined to obtain specimens for mechanical testing. Inconel 718 specimens were thermally over-aged from 600 °C to 750 °C (± 1 °C temperature accuracy) with a temperature exposure of up to 10,000 hours. For Waspaloy, thermal over-aging conditions ranged from 750 to 850 °C with a holding time of up to 10,000 hours.

Several mechanical tests were performed in order to characterize the specimens after thermal exposures. Hardness characterizations were performed at room temperature. Brinell hardness measurements HRB 2.5/187.5 (*i.e.,* indentation at 1.8 kN load using a 2.5 mm diameter tip) were done for each sample, after mechanical polishing to a mirror finish to remove the effect of roughness. Five indentations (at least) per specimen were carried out and an arithmetic average value was calculated. Tensile tests were performed at temperatures ranging from 200 °C up to 850 °C (depending on the alloy) using an electro-mechanical machine using a strain rate of 8.3×10^{-4} s^{-1}. It is to note that necking occurred in all samples. Hence, the ultimate tensile strength (UTS) values correspond to the maximum stress before the occurrence of necking. It was observed that the higher the temperature, the higher the extent of necking.

Fatigue tests (sinusoidal waveform, strain control mode, strain ratio = 0, frequency = 0.2 to 2 Hz) were performed at 650 °C for Inconel 718 samples and 750 °C for Waspaloy samples. After 85,000 cycles at 0.2 Hz in strain control mode, fatigue tests were switched to stress control with a frequency of 2 Hz with the stress ratio defined by the minimum and maximum stabilized stresses obtained during the first part of the test in strain control mode.

Finally, scanning electron microscope was used to characterize the precipitates evolution after thermal over-aging treatments and to observe failure mechanisms in LCF. Both a JEOL JSM 7000F and a ZEISS Sigma HD-VP field-emission gun scanning electron microscopes, operating in the 20 to 25 kV high tension range have been used. Quantitative image analysis with the software Visilog was performed to measure the size of the precipitates.[38]

III. RESULTS

The mechanical properties of Inconel 718 and Waspaloy samples before over-aging are shown in Table II. In the following sections, mechanical results will be plotted as normalized values in order to highlight the impact of over-aging with respect to the initial (optimized) properties of the two alloys

A. *Hardness*

The impact of thermal over-aging on mechanical properties can be easily observed *via* room temperature hardness measurements. Figure 1 shows that long-term over-aging at 650 °C up to 10,000 hours has almost no impact on the hardness of Inconel 718. On the contrary, over-aging at 700 °C has a noticeable impact on hardness that drops rapidly by 10 pct from its initial value after 1000 hours and then slowly decreases up to 10,000 hours, dropping again by 10 pct with respect to the initial state. As expected, the most remarkable evolution of hardness in Inconel 718 is observed at 750 °C, which is a temperature higher than the maximum temperature of the standard direct aging treatment (8 hours at 720 °C followed by 8 hours at 620 °C, air cooling). In fact, after over-aging at 750 °C for 1000 hours, the hardness drops by almost 30 pct and then it barely decreases after 3000 hours. The observed trends are in good agreement with a previous work from

Table I. Typical Compositions of Inconel 718 and Waspaloy (Weight Percent)

Alloy	Ni	Cr	Mo	Fe	Nb	Ti	Al	Co	B	C
Inconel 718	bal.	19.0	3.1	18.5	5.2	0.9	0.55	—	0.005	0.05
Waspaloy	bal.	19.0	4.0	—	—	3.0	1.9	13.5	0.005	0.07

Table II. Mechanical Properties of Inconel 718 and Waspaloy Before Over-Aging

Alloy	Hardness at Room Temperature (HRB)	Ultimate Tensile Strength at 650 °C (MPa)	Yield Strength at 650 °C (MPa)	Rupture Elongation at 650 °C (Pct)
Inconel 718	439	1205	1056	24
Waspaloy	378	1201	889	15

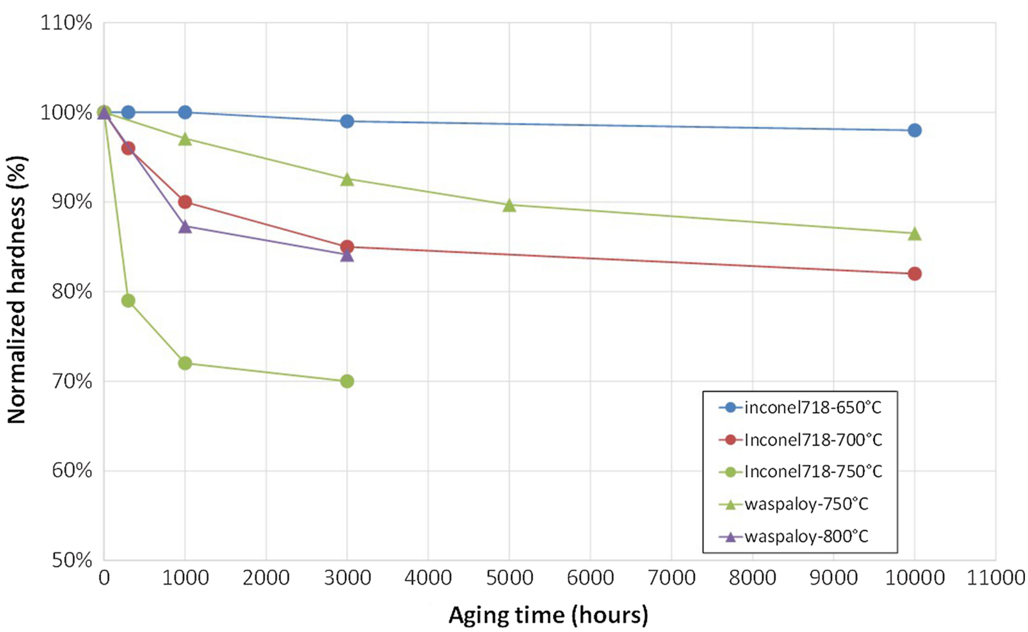

Fig. 1—Impact of different thermal over-aging conditions on Waspaloy and Inconel 718 room temperature hardness.

Andrieu *et al.*[39] The interested reader is also referred to a previous article from the authors to get a better understanding of the effect of long-term thermal exposures in a wider temperature range on direct-aged Inconel 718 room temperature hardness.[10]

The investigated over-aging temperatures of both alloys are not the same since the temperatures of interest and the mechanical properties stability of both alloys are different. However, it is interesting to compare the results of Inconel 718 with those obtained on Waspaloy after over-aging at 750 °C. Hardness of Waspaloy drops only by 5 pct after 1000 hours and by 15 pct after 10,000 hours. These results at 750 °C illustrate well the higher stability in hardness of Waspaloy with respect to Inconel 718 in the same over-aging conditions. Moreover, Figure 1 shows that the evolution of the hardness of Inconel 718 up to 3000 hours at 700 °C is similar to that of Waspaloy at 800 °C, which is a temperature 100 °C above the over-aging temperature of Inconel 718.

B. *Tensile Resistance*

Hardness measurements show if a material is sensitive to thermal over-aging. However, in order to perform a reliable life design of a component whose material is sensitive to long-term annealing, it is necessary to characterize materials at high temperatures after different given states of microstructure degradation. Figure 2 shows the impact of different thermal over-aging conditions on Waspaloy and Inconel 718 tensile properties at 650 °C.

Similarly to the evolution of hardness, yield stress (YS) and ultimate tensile strength (UTS) are found to decrease with longer and hotter over-aging conditions

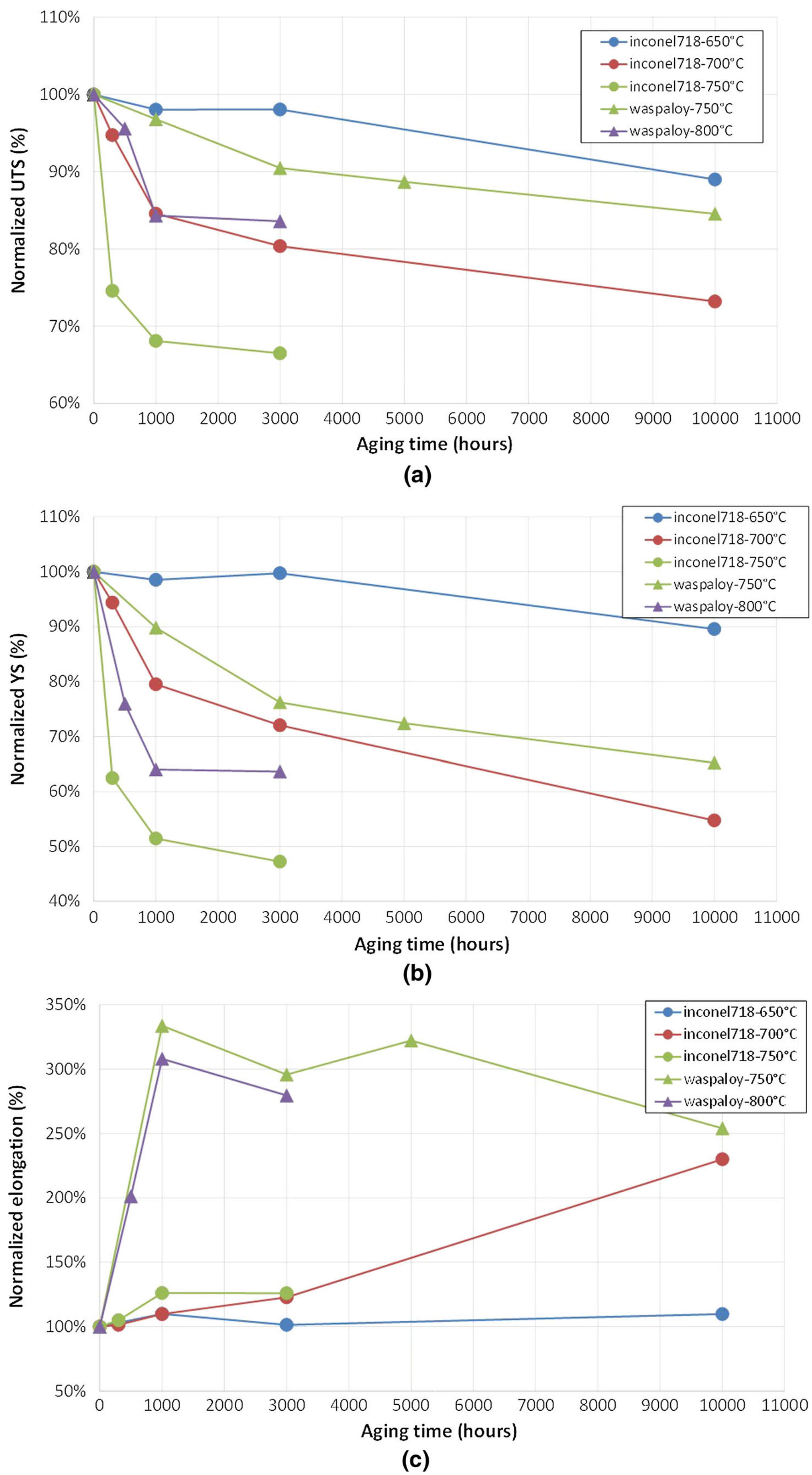

Fig. 2—Impact of different thermal over-aging conditions on Waspaloy and Inconel 718 tensile properties at 650 °C: yield stress (*a*), ultimate tensile stress (*b*) and strain at failure (*c*).

(see Figures 2(a) and (b)). However, the impact of over-aging on YS and UTS is more noticeable compared to its effect on room temperature hardness. For example, in the case of Inconel 718 after over-aging at 650 °C for 10,000 hours, the YS (or UTS) drops by 10 pct, while the hardness does not show any significant decrease. Moreover, after over-aging at 750 °C for 3000 hours, the YS of Inconel 718 drops by 50 pct, while the hardness decrease is only 30 pct. As expected, the comparison of UTS or YS results of Waspaloy and Inconel 718 confirms the higher stability of the former. In particular, the evolution of the UTS of Inconel 718 up to 3000 hours at 700 °C is similar to that of Waspaloy at 800 °C, which is a temperature 100 °C hotter than the over-aging temperature of Inconel 718. However, the evolution of the YS of Inconel 718 up to 3000 hours at 700 °C is closer to that of Waspaloy at 750 °C, reducing then the "equivalent stability" temperature gap between the two alloys. It is interesting to note that, except at 650 °C for Inconel 718, almost continuous decreases in YS and UTS are observed in Figures 2(a) and (b).

Figure 2(c) shows that all over-aging conditions induce an increase of the elongation at failure with respect to the initial state before over-aging. In the case of Inconel 718, the maximum rupture elongation increase (+ 225 pct) is observed at 700 °C after 10,000 hours, while for Waspaloy (+ 325 pct) it is observed at 750 °C after only 1000 hours. It is then interesting to note that the evolution of ductility as a function of time is not necessarily monotonous for Waspaloy (or Inconel 718 after over-aging at 650 °C) as the one observed for UTS or YS results. One should also notice that no steep decrease in strain at failure has been observed, as expected since these two alloys are stable with respect to the precipitation of brittle TCP phases.[7,8,11,12]

C. *Fatigue Performance*

The impact of thermal aging on low cycle fatigue (LCF) life is shown in Figure 3. For both alloys, all over-aging conditions that were found to be detrimental to tensile properties do not necessarily decrease the fatigue life. For example, over-aging hardly affects Inconel 718 LCF life at 650 °C in the normalized stress range 0.45 to 0.6. Three points are lying outside of the main trend, with a LCF life debit of a factor 3 to 4, especially for the longest over-aging at 700 °C (see Figure 3(a)). However, if the normalized stress range is higher than 0.6, then over-aging significantly decreases the LCF life with respect to specimens in the optimized (as-received) state. The decrease of the number of rupture cycles after over-aging is almost systematically attributed (as confirmed by fracture SEM analysis which are presented in a subsequent part of this article) to the occurrence of surface crack initiation in over-aged specimens (see circled points in Figure 3(a)), while internal crack initiation occurs in specimens without over-aging. This finding then suggests that over-aging would promote the occurrence of surface initiation in LCF tests. It is here worth recalling that over-aging has been conducted on blanks before machining of the specimens and that the decrease in LCF life does not result from the presence of an oxide scale/oxide spikes at the beginning of LCF tests.

A different reduction in life behavior is observed from the analysis of Waspaloy LCF results at 750 °C (Figure 3(b)). If the normalized stress is higher than 1, then results with or without over-aging are all comparable. If the normalized stress range is lower than 1, then over-aging appears to decrease LCF life by promoting surface initiation. However, the effect of over-aging is less visible for this alloy.

D. *Microstructure Observations*

As mentioned earlier, the high-temperature resistance of Inconel 718 and Waspaloy is mainly derived from the presence of fine (20 to 200 nm) hardening precipitates (γ'' and/or γ') that directly affect the mechanical properties as a function of their size and distribution. Concerning the γ'' phase, it is worth noting that it is a metastable phase that transforms during over-aging into its stable phase (δ phase).[10,18,40] In the case of Waspaloy, only γ' precipitates are present in the microstructure after the standard aging heat treatment. The γ' precipitates can be classified in three groups according to their origin and size: primary ones (size of few microns) are formed during the manufacture of the billet, secondary ones (average size of 200 nm) during the cooling following the solution heat treatment, and tertiary ones (average size of 20 nm) during the aging heat treatment.[11,23,41]

Figure 4 shows the typical microstructure of the two alloys after the standard aging treatment and the evolution of γ' and γ'' precipitates after thermal over-aging at 750 °C for 1000 hours. In the case of Waspaloy, over-aging induces the coarsening of secondary γ' precipitates at the expense of tertiary ones that coarsen and then dissolve (compare Figures 4(a) and (b)). Also, in Inconel 718, over-aging induces the coarsening of both γ' and γ'' precipitates but the kinetics of coarsening and transformation of γ'' particles to the δ phase is so rapid that after 1000 hours at 750 °C, all γ'' precipitates have been transformed to δ phase (see Figure 4(d)), in good agreement with previous articles on alloys 718 or 625.[18,39,42] More observations of over-aged Inconel 718 specimens in different conditions are available in Jouiad *et al.* article.[10] It is also worth noting that during over-aging, the shape of γ'' precipitates changes from a spheroidal one to a lenticular one leading eventually to the coalescence with other precipitates to form rod-like δ particles. As a consequence, the volume fraction of the δ phase increases during over-aging. For example, after 1000 hours at 750 °C, the area fraction of δ phase increases from 4 to 16 pct (see Figure 5).

Overall, from all the observations performed on both alloys, no obvious evolution of grain size or primary/secondary carbides has been detected within the temperatures and durations investigated. Hence, the evolutions in tensile, LCF, and hardness properties cannot be attributed to these parameters.

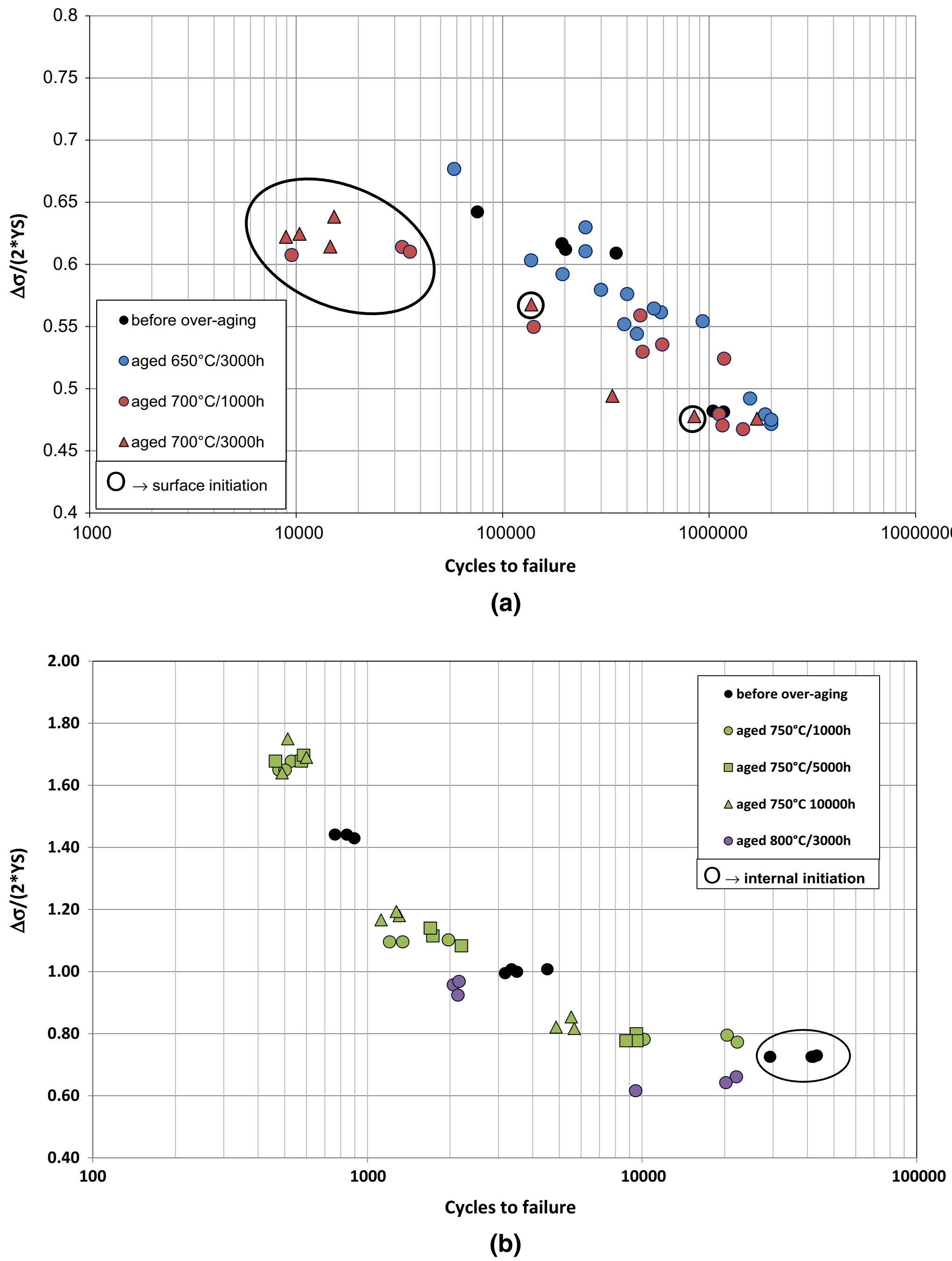

Fig. 3—S–N diagram after different thermal over-aging conditions on Inconel 718 at 650 °C (*a*) and Waspaloy at 750 °C (*b*).

Based on several SEM observations, it has been possible to plot the evolution of average γ' and γ'' particle size as a function of different thermal over-aging conditions (Figure 6). It is worth noting that in Waspaloy only secondary γ' precipitates could be measured and for Inconel 718 the size of γ'' precipitates corresponds to the longest dimension of the lenticular shape.

Coarsening of γ' and γ'' particles has occurred in both alloys, but kinetics are quite different. In the case of Waspaloy, the kinetics is quite slow at 750 °C or 800 °C as the size of secondary γ' precipitates increases from about 190 nm up to 210 or 220 nm, respectively. However, it is important to note that at the same, tertiary γ' precipitates also coarsen and then dissolve in this alloy. In Inconel 718, both the kinetics of coarsening of γ' and γ'' particles are faster than the one observed in Waspaloy. The fastest evolution is observed at 750 °C where the size of γ' particles increases from 20 nm to almost 150 nm after 3000 hours while the size of γ'' particles increases up to 230 nm after only 300 hours. In

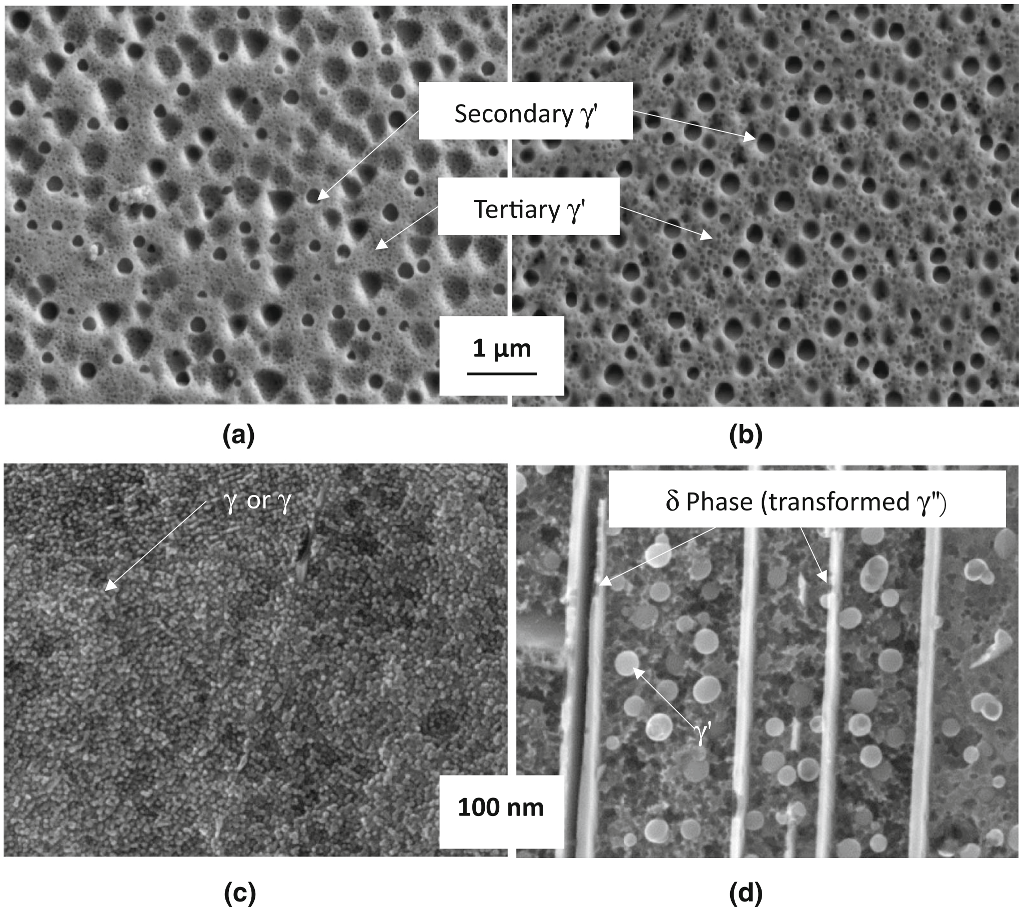

Fig. 4—γ' and γ'' particles in Waspaloy in the as-received state (*a*) and after 1000 hours at 750 °C (*b*) and γ'', δ, and γ' particles in Inconel 718 in the as-received state (*c*) and after 1000 hours at 750 °C (*d*).

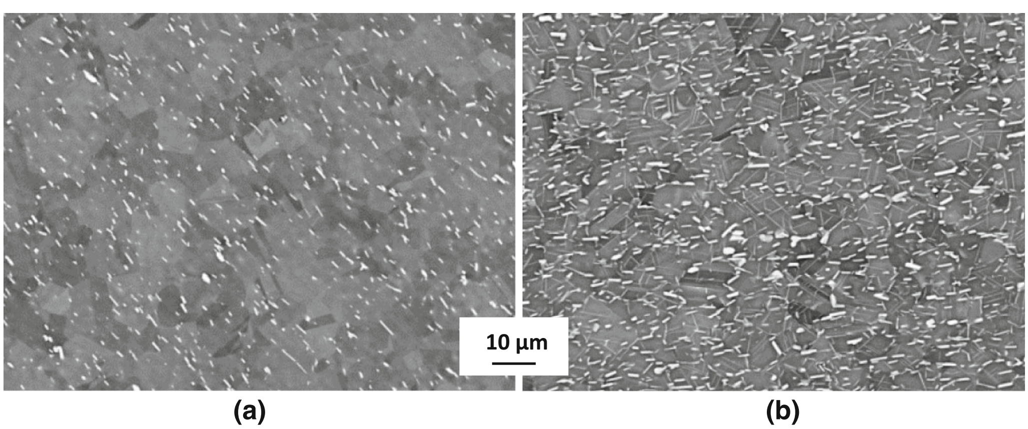

Fig. 5—Evolution of the δ phase surface fraction before (*a*) and after (*b*) 1000 hours at 750 °C.

fact, the coarsening (and transformation into δ phase) of γ'' particles is so rapid that after 1000 hours at 750 °C the γ'' precipitates can be no longer observed.[18,39,40,43]

Overall, the coarsening process of γ' or of γ'' particles appears to be consistent with the Lifshitz, Slyozov & Wagner (LSW) theory, since a linear relation could be found between D^3 and t, where D is the average particle diameter and t is the over-aging time (not shown in this article). These results are in good agreement with previous articles investigating precipitates coarsening in both alloys.[9,11,46]

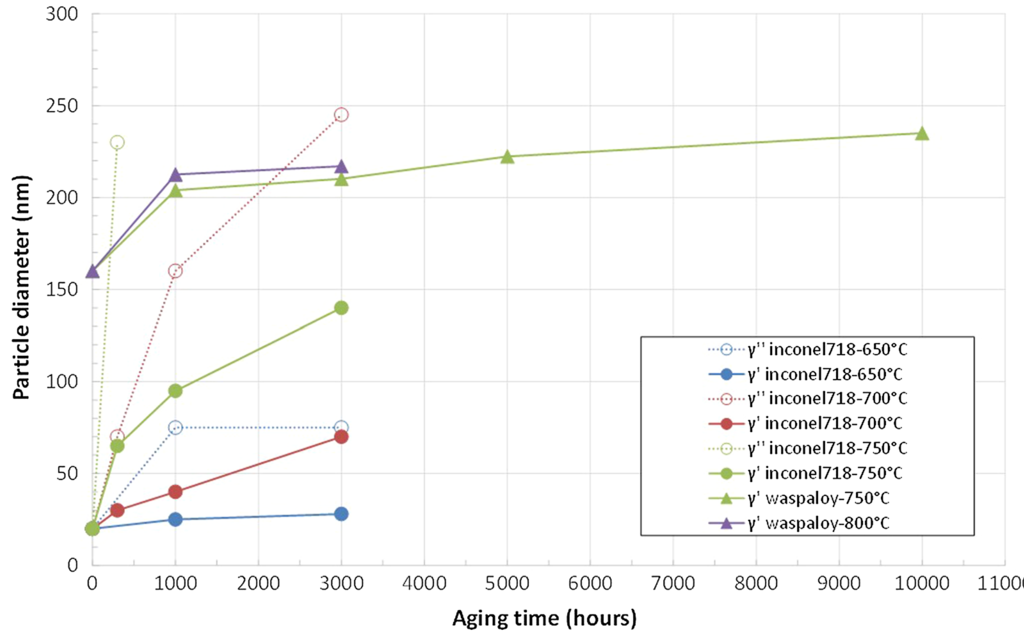

Fig. 6—Evolution of γ' and γ'' particle size as a function of different thermal over-aging conditions.

IV. DISCUSSION

The main conclusion that can be drawn from Figure 2 is that Waspaloy tensile strength is significantly less sensitive to over-aging above 700 °C compared to Inconel 718. Moreover, both alloys exhibit an equivalent stability over time (in terms of tensile properties) if the over-aging temperature of Waspaloy is 50 °C to 100 °C higher than that of Inconel 718. As suggested by Figure 6, the higher stability of Waspaloy can be attributed to the slower kinetics of coarsening and dissolution of γ' precipitates compared to γ'' precipitates, that account for the majority of hardening particles in Inconel 718. In fact, γ'' particles are known to grow faster due to their large coherency with the matrix and, then, to transform into δ phase.[8] Larger precipitate–matrix lattice mismatch in magnitude, if beneficial to static properties such as yield stress and creep resistance,[6,39,44,45] are also known to lead to faster coarsening kinetics, by inducing larger lattice distortion in the vicinity of the precipitate/matrix interface.[10,46–49] However, the progressive decrease in tensile properties observed for both alloys due to particle coarsening is not accompanied by a decrease in tensile ductility (see Figure 2(c)). Both alloys are indeed known to be stable with respect to intermetallic (brittle) phase formation at grain boundaries such as TCP phases, including Laves phase, which are generally known to decrease tensile ductility.[7,11] In the case of Waspaloy, the progressive transformation of primary to secondary carbides previously characterized[50] has not been observed to affect tensile ductility.

Regarding fatigue properties, the most striking result from Figure 3 is that over-aging decreases the number of cycles to failure by promoting surface crack initiation. Figure 7(a) shows that internal crack initiation at an internal non-metallic particle (TiN) is obtained in nearly all experiments, in good agreement with results of Texier *et al.*[30,31] However, surface crack initiation at a particle or a grain is favored by a prior over-aging, as observed in Figure 7(b). Similar observations were found for Waspaloy where cracks initiate from internal (Figure 7(c)) or surface (Figure 7(d)) coarse grains without and with prior over-aging, respectively. However, further LCF results in Figure 3(b) would have been however necessary to confirm this trend. These crack initiation locations at high temperature are in good agreement with previous studies on LCF strength of both alloys.[23,26]

To better understand this change in crack initiation location with prior over-aging, one has also to consider the consequences of over-aging on the cyclic behavior, since fatigue tests were performed under strain-controlled mode. Concerning the impact of over-aging on fatigue behavior, it is interesting to analyze the evolution of stress during tests under the same strain control condition. Figure 8 shows the maximum stress and stress amplitude evolutions for both alloys without and with different over-aging durations. Strain hardening is observed for Inconel 718 specimens (Figure 8(b)), except in the un-aged Inconel 718 specimen for which first cyclic hardening followed by cyclic softening is observed. For Waspaloy, either softening or stable stress amplitudes are observed (Figure 8(d)). These observed cyclic behaviors are in quite good agreement with previous literature for the considered LCF testing conditions.[23,26] However, for both alloys, it is observed that a progressive decrease in the maximum stress occurs with increasing number of

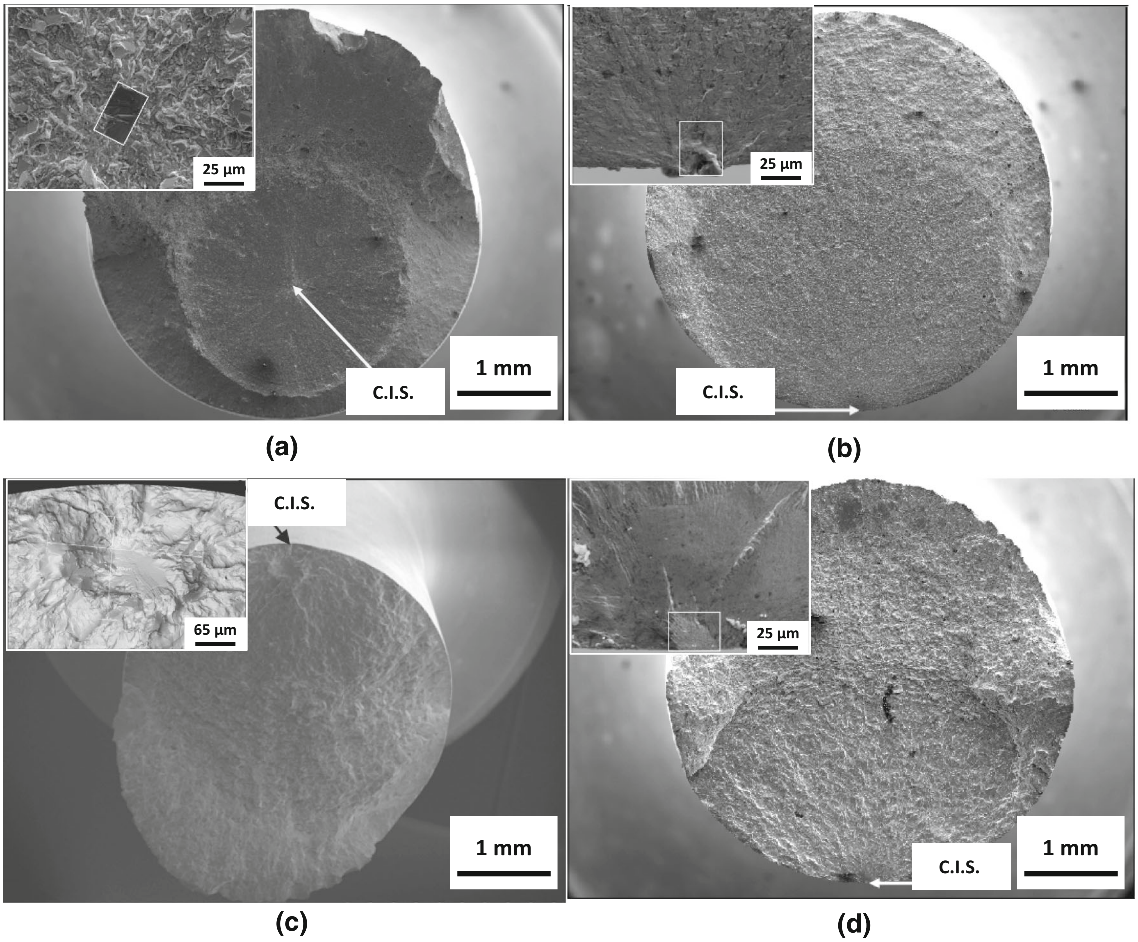

Fig. 7—Typical fractographic observations of Inconel 718 samples tested in LCF at 650 °C before over-aging (*a*), after 3000 h at 700 °C (*b*) and of Waspaloy samples tested in LCF at 750 °C before over-aging (*c*), after 3000 h at 800 °C (*d*). Crack initiation sites (C.I.S.) have been indicated on each figures and a magnification on the crack initiation site has been provided as insert in each cases.

cycles, a decrease which is more pronounced when the over-aging duration is increased. Given the stress amplitude evolutions, it means that a mean stress relaxation occurs and that this stress relaxation is much more pronounced when increasing the prior thermal exposure. Finally, one should also note that the macroscopic signature of crack initiation and propagation (*i.e.,* final decrease of maximum stress in Figures 8(a) and (c)) occurs at the very end of the LCF life. The detected crack propagation stage hence occupies no more than 5 to 10 pct of the total LCF life (whatever the test) and the observed impact of over-aging on the total LCF mainly results from an effect on the crack initiation stage, rather than on the (long) crack propagation one.

From the cyclic behavior observed in Figure 8, one could have expected to obtain increased LCF lives if the crack initiation sites would have remained the same since maximum stresses are lower after over-aging. However, it is observed that over-aging favors crack initiation at the surface, which lowers LCF lives (see Figure 3). It hence suggests that the environmental sensitivity of both alloys is increased after over-aging. For Waspaloy, crack initiation at temperatures equal to, or in excess of 700 °C usually occurs at the surface if LCF lives are long enough.[23] At such a high temperature, LCF life is controlled by the oxidation in Waspaloy. This is also observed in our case, except for very long LCF lives (*i.e.,* low applied strain amplitudes) for which sub-surface crack initiation occurs at a coarse grain can be obtained. The prior over-aging hence accelerates intergranular crack initiation, probably through an increased grain boundary precipitate free zone, in addition to the precipitation/transformation of carbides.[12,50] This assumption still remains to be further investigated, since no obvious evolution of primary/secondary carbides has been detected. In Inconel 718 (or 625), similar precipitate-free zones close to grain boundaries have already been found,[17,40] which probably favor earlier crack initiation, in addition to an increased oxidation sensitivity.[26,51,52] Moreover, the $\gamma'' \rightarrow \delta$ transformation is also understood to control crack initiation mechanisms as well as crack propagation rate in alloy 718.[31,53,54]

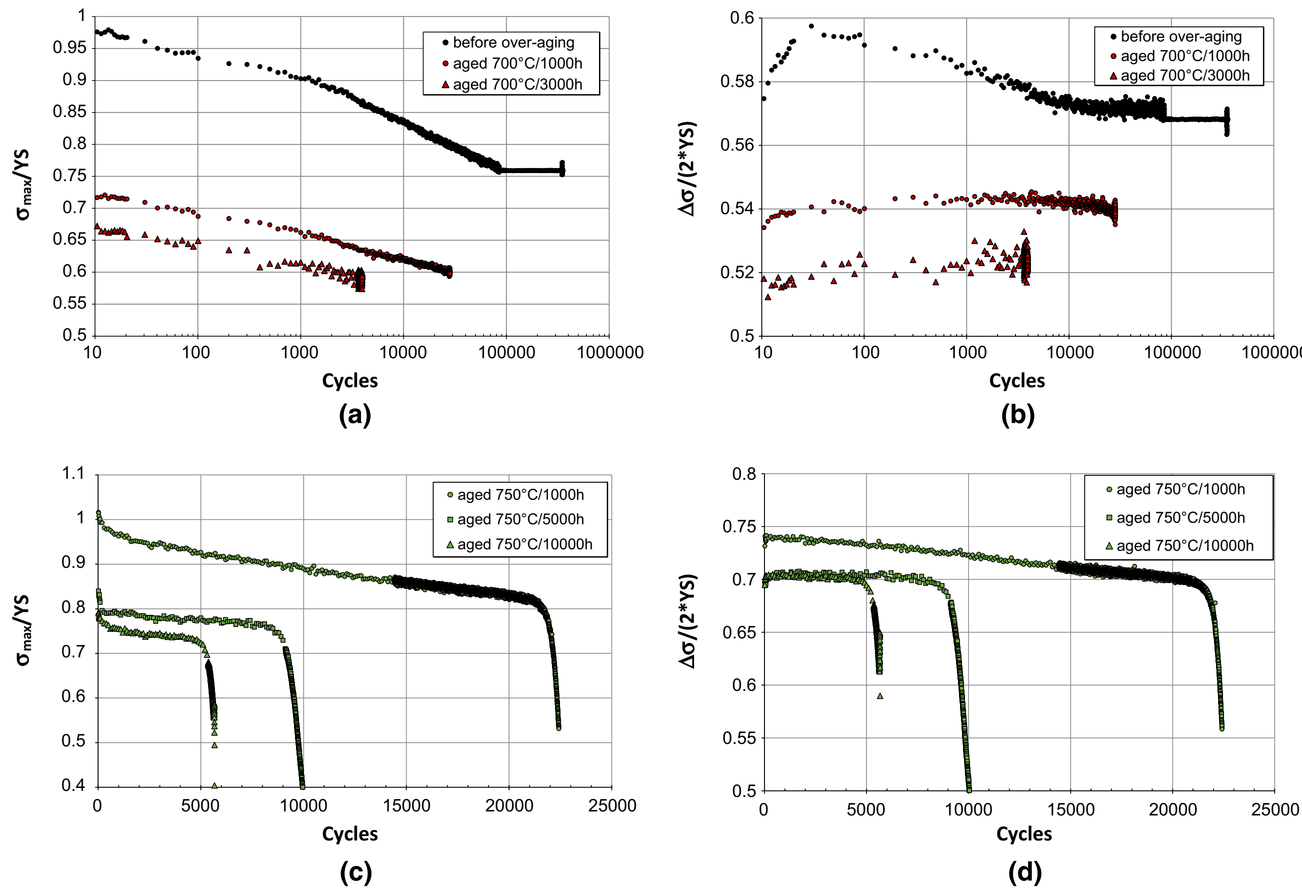

Fig. 8—Impact of over-aging on the LCF cyclic behavior of Inconel 718 at 650 °C (*a*, *b*) and of Waspaloy at 750 °C (*c*, *d*).

V. CONCLUSIONS

The impact of thermal over-aging (in the temperature 600 °C to 850 °C and duration 300 to 10,000 hours ranges) on the mechanical properties (hardness, tensile properties, fatigue) of Inconel 718 and Waspaloy forgings has been studied.

The comparative analysis of tensile results of both alloys indicates that Waspaloy has a better thermal stability compared to Inconel 718. Equivalent loss of tensile properties is achieved for both alloys if the over-aging temperature is increased by nearly 100 °C for Waspaloy. The higher stability of Waspaloy is attributed to the slower kinetics of coarsening and dissolution of γ' precipitates compared to γ'' precipitates, which are the main strengthening particles in Inconel 718.

Fatigue results indicate that in both alloys, over-aging promotes a faster relaxation of the mean stress due to the coarsening of strengthening precipitates. Moreover, surface crack initiation is favored by over-aging, thus leading to shorter fatigue life.

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