TENSILE AND CREEP STRENGTH OF THERMALLY EXPOSED ALLVAC 718PLUS

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Keywords: Thermal Stability, Creep strength, Tensile strength

Abstract

The novel alloy Allvac 718Plus shows superior thermal stability in comparison to Alloy 718 but maintains desirable workability and weldability. In literature, it is often claimed that the maximum operating temperature of Allvac 718Plus is in the range of 700°C, gaining the level of Waspaloy and Udimet 720Li. The purpose of this study is to define the limit of the temperature capability of Allvac 718Plus.

Material was thermally exposed at temperatures in the range of 650 to 680 °C for 500h and tested regarding its tensile and creep behavior. The microstructures before and after exposure were investigated by SEM and TEM to observe changes due to dissolution and coarsening of γ' and formation and growth of δ/η -phase. The results show that a thermal exposure up to 680 °C has no detrimental effect on the mechanical properties, which confirms a thermal capability at least of 680 °C. Additionally, long term creep tests were carried out to investigate the influence of applied stress during thermal exposure. The results indicate that the degrading mechanisms are accelerated by an applied load analogue to alloy 718.

Introduction

More than fifty years after the introduction alloy 718 is still one of the most widely used nickel-based superalloys for aerospace applications due to the excellent balance of mechanical properties, moderate costs, castability, forgeability and weldability. In the year 2000 alloy 718 accounted more than fifty percent of the superalloys used in GE Aviation [1] and Pratt & Whitney [2] engine forgings. Despite the overwhelming success, the metastability of the strengthening phases has always been considered as a drawback of alloy 718 and limited the temperature capability up to 650 °C. The trend towards higher operating temperatures associated with increased compressor and turbine efficiency raised the demand for a new low cost, high temperature structural material with maximum application temperature around 700 °C [1]. Novel alloy Allvac 718Plus (718Plus) seems to fulfill these requirements retaining the processing characteristics of alloy 718 and possessing a thermal stability on the level of competing alloys like Waspaloy [3-5]. By achieving this goal, 718Plus became not only a promising candidate for static structural parts in aircraft turbine engines but also for rotating components like high pressure turbine discs [6-8]. For the application as rotating part the thermal stability of 718Plus becomes even a more critical criterion.

The thermal stability in alloy 718Plus strongly depends on the structure and composition of the precipitation hardening phases. Modifications in the composition, especially of the Al and Ti content [9], lead to the γ' -phase (Ni_3Al ; L1_2) as primarily strengthening phase compared to γ'' -phase (Ni_3Nb ; DO_{22}) in alloy 718.

While some publications showed evidences of the co-existence of γ'' -particles to a minor content [10-13] other studies couldn't confirm the presence of γ'' -phase in 718Plus [8,14-18]. Cao [7,12] observed sandwich-structured γ' -particles, having a middle layer of supposedly γ'' -phase, in particular subsequently to thermal exposure.

Similarly, such co-existences of γ' - and γ'' -phase in compact morphologies [19] have already been found for alloy 718 derivatives and could possibly explain the contradictory results regarding the presence of γ'' in 718Plus. Simultaneously the chemical modification in 718Plus lead to a stabilization of hexagonal η -phase (Ni_6AlNb ; D0_{24}) over the orthorhombic δ -phase (Ni_3Nb ; D0_a) present in alloy 718, as secondary precipitates [16,20,21]. Pickering et al. [16] confirmed earlier studies about the existence of η -phase [13,22] by detecting that the plate-like precipitates consist mainly of η -phase, only interrupted by very fine δ -stripes. All this contradictory observations lead to the assumption that the structure and composition of the precipitated phases strongly depends on the mechanical processing and heat treatment of the material. Consequently the thermal stability of 718Plus would be affected by the thermo-mechanical history as well.

Therefore, the thermal stability of a completely forged and heat treated turbine disc was investigated by long term exposure of the material close to the anticipated maximum application temperature around 700 °C [5]. Mechanical tests and metallographic examinations before and after thermal exposure were performed in order study the degree of degradation and the apparent damaging mechanism.

Materials and Experimental Procedure

Materials

For investigation of the thermal stability of 718Plus Rolls-Royce Deutschland Ltd. & Co KG provided a completely forged and fully heat treated turbine disc. The original wrought billet was processed by ATI Allvac, USA and forged to final geometry in several sub-solvus forging steps and subsequently heat treated by Otto Fuchs KG, Germany. The standard heat treatment included different stages, starting with pre-solution heat treatment (PSHT), γ' -solution heat treatment (SHT) and finishing with a double γ' -aging step. The standard heat treatment details like temperature and time were based on the recommendations of ATI Allvac [23]:

- PSHT: 843°C - 871°C for 16h, Air Cool or Raise to SHT
- SHT: 954°C for 982°C for 1h Maximum, Air Cool or Faster
- Aging: 788°C for 2 - 8h, Furnace Cooling + 704°C for 8h Air Cool

The chemical composition of the analyzed 718Plus material compared to nominal chemistry of alloy 718 is presented in Table 1.

Table 1: Chemical composition of the 718Plus material investigated in this study compared to the nominal composition of alloy 718 in wt %.

Element	Ni	Cr	Mo	W	Co	Fe	Nb	Ti	Al	C	P	B
718Plus	Bal.	18.0	2.8	1.1	9.0	9.0	5.5	0.7	1.5	0.025	0.012	0.006
718	Bal.	18.1	2.9	-	-	18.0	5.4	1.0	0.5	0.025	0.007	0.004

The heat treated disc was separated in several similar parts having the same geometry to ensure that the specimens for mechanical testing come from identical positions within the disc. By maintaining the exact same position the influence of local changes of the microstructure within the turbine disc can be neglected.

Thermal exposure

Similar parts of the turbine disc after the standard heat treatment were exposed to different long term heat treatments close to the maximum anticipated working temperature of around 700 °C (see Table 2). To detect the degree of degradation, the heat treated material was compared to the unexposed reference (Ref). Exposure temperatures of 670 °C (TE670) and 680 °C (TE680) have been chosen to identify when degrading mechanism start to influence the mechanical properties and the maximum application temperature is reached. Additionally, long term thermal exposure (LTE650) at 650 °C for 2000 h has been performed as well. According to studies on alloy 718 [24,25] long time exposure at 650 °C led to reduced strength and creep properties although no degradation could be observed after 500 h. In order to simulate a more realistic scenario for the exposure of a turbine disc, thermal exposure was combined with mechanical loading. This test (STE670) should clarify, if an analogue to the alloy 718 degradation mechanism happens during thermal exposure which is accelerated by the presence of mechanical stress [26,27].

Table 2: Variant heat treatment conditions of 718Plus investigated in this study.

Abbreviation	Standard heat treatment	Thermal exposure heat treatment		
		Temp./°C	Time/h	Applied external stresses/MPa
Ref	X	-	-	-
TE670	X	670	500	-
TE680	X	680	500	-
LTE650	X	650	2000	-
STE670	X	670	500	350

Mechanical Testing

With respect to turbine disc application the crack propagation behavior, LCF life, creep and tensile strength are important. Earlier studies showed that thermal exposure at 760 °C isn't deleterious for LCF life and crack propagation behavior (with and without dwell) [28]. In consequence only the effect of thermal exposure on room (RTT) and elevated temperature (ETT) tensile strength at 650 °C as well as the creep properties are examined. Creep experiments were performed on the different sample variants at 650 °C for two different conditions, high stresses of 800 MPa and intermediate stresses of 650 MPa. The influence of stress during thermal exposure was investigated by performing long term creep tests at relatively low stresses before testing at high stresses. For the sample STE670 a mechanical load of 350 MPa was selected and the creep test was interrupted after 500 h. The stress was calculated in the way that plastic deformation during testing doesn't exceed 1 % and consequently the generation of creep damage is avoided.

Metallographic examinations

Before examining the microstructures in a scanning electron microscope (SEM) Zeiss Crossbeam 1540, the samples were surface finished by polishing with an active oxide suspension (OP-U Suspension, Struers). The images were taken using an acceleration voltage of 20 kV and detecting backscattered electrons (BSE) at a working distance of 7.5 mm.

The grain size distribution was measured by the linear intercept method using the software ImageC on four pictures (60 μm x 40 μm). The characterization of the area fraction of η -phase was performed by using the open source software ImageJ. The pictures were converted to binary maps by manually adjusting the threshold value. Afterwards the accuracy of this converting step was controlled by comparing carefully the binary map and original picture. For evaluation of η -phase content, the area fraction of four pictures (60 μm x 40 μm) have been averaged.

For characterizing the size of γ' -precipitates the variants have been investigated by means of transmission electron microscopy (TEM). The TEM samples were thinned by mechanical grinding to a thickness of around 150 μm . Small discs, 3 mm in diameter, were subsequently electropolished with an electrolyte solution containing 8 % perchloric acid and an applied voltage of 40 V and temperature of -30 °C. The thinned electron transparent samples were investigated using a Philips CM200 TEM at 200 kV. Investigations were performed in the bright field mode and imaging was done via the installed 2k x 2k CMOS camera F216 (TVIPS). It has to be noted, that SEM and TEM samples were removed from exactly the same position within the disc. Differences regarding the evolving temperature while forging the disc, lead to varying microstructure regarding η -phase fraction and grain size. By keeping the position of the sample the influence of local changes in the microstructure due to forging is neglected.

Results

Grain size and η -area fraction

Detailed metallographic analysis was performed on the unexposed reference and the sample additionally heat treated at 680 °C (TE680). In figure 1 the SEM images before and after thermal exposure are shown.

Figure 1: SEM micrograph of the microstructure of the standard heat treated reference material and the additionally thermally exposed material at 680 °C for 500 h.

In both conditions the grain structure shows a uniform equiaxed grain morphology without any significant texture. The reference has a median grain size of 2.6 μm . In comparison, the exposed state has a similar grain size distribution with a median grain size of 2.9 μm (Table 3).

Table 3: Grain size and η -area fraction of the unexposed reference compared to the thermally exposed sample (680 °C, 500 h).

State	Grain size / μm (Median $\pm \sigma$)	η -Area Fraction / % (Average $\pm \sigma$)
Ref	2.6 ± 2.3	8.8 ± 0.3
TE680	2.9 ± 2.3	8.7 ± 0.2

If further η -phase is formed during thermal exposure has been analyzed by evaluating the area fraction of η -phase for both states. The morphology of present η -phase is the well-known plate-like structure. The relatively coarse (median width: 0.3 μm) and long plates (median length: 1.6 μm) are primarily decorating the grain boundaries. Besides this plate-like precipitates, often η -phase with lamellar morphology, discontinuously grown into the grains, has been observed [8,16,22]. This type of thin lamellae is only present to a very minor content in the studied material. The area fraction of η -phase is around 8.8 % for the reference and 8.7 % for the exposed material. Considering the accuracy of the measurement, no increase of η -phase fraction could be observed.

The TEM investigate in figure 2 show the γ' -particles for the unexposed and the thermally exposed material. The γ' -particles have a spherical morphology of uniform size. In accordance to earlier TEM investigations [28,29] no coarse primary or fine tertiary γ' -particles could be detected.

Figure 2: Spherical, monomodal distributed, γ' -morphology observed for the reference (left) and exposed state (680°C/500h) (right).

Comparing the size of the γ' -precipitates before and after thermal exposure no significant coarsening of particles happens during thermal exposure at 680 °C. The reference shows a relatively narrow distribution of γ' -particles with an estimated median size of 35 nm. In the exposed state the particles seem to be slightly coarsened in comparison to the reference state. Further detailed analyses are necessary to confirm this observation.

Effect of thermal exposure on the mechanical properties

As mentioned earlier this study concentrates on the effect of thermal exposures on room (RTT) and elevated temperature (ETT) tensile strength at 650 °C. In Figure 3 the results of RTT test are shown. Therefore the yield stress $R_{p0,2}$ and ultimate tensile strength R_m of the exposed states has been related to the unexposed reference. Obviously yield and ultimate tensile strength are slightly increased in all heat treated states. Consequently the mechanical properties seem not to be degraded by any of the investigated thermal exposure heat treatments. Similarly, the influence of different exposure heat treatments on the ETT properties at 650°C is shown in Figure 4.

Figure 3: Effect of different thermal exposures on the room temperature tensile properties. The yield stress $R_p^{Exposed}$ and tensile strength $R_m^{Exposed}$ of the exposed material are related to the unexposed state R_p^{Ref} and R_m^{Ref} .

Figure 4: Effect of different thermal exposures on the elevated temperature tensile properties. The yield stress $R_p^{Exposed}$ and tensile strength $R_m^{Exposed}$ of the exposed material are related to the unexposed state R_p^{Ref} and R_m^{Ref} .

Similar to RTT tests the tensile properties at elevated temperatures aren't affected significantly by thermal exposure. However, contrary to RTT tests, exposing at 680 °C leads to a slightly degraded yield and ultimate tensile. However, the degradation of yield and ultimate tensile strength is less than 2 %.

The effect of thermal exposure on the creep behavior at a test temperature of 650 °C and stresses of 800 MPa and 650 MPa is shown in Figure 5. With respect to application, the creep rate at the early stage of deformation, i.e. the primary creep stage and the following creep minimum are of great importance. Figure 5 (b & d) shows that mainly the creep behavior at small plastic strains is influenced by thermal exposure. The most negative effect on the creep strength has the thermal treatment at the highest temperature of 680 °C.

Figure 5: Creep behavior of reference and differently exposed material at test temperature of 650 °C and applied stresses of 800 MPa (a; b) and 650 MPa (c; d). The creep experiment at 650°C/800MPa was repeated for the reference to show the accuracy of the test procedure. By plotting the logarithmic creep rate as a function of plastic strain (b & d) the increase of the minimum creep rate for the exposed state becomes apparent.

Additionally the effect of stress assisted thermal exposure on the creep properties was tested by performing long term creep experiments. Subsequent to the long term creep experiments at 350 MPa the standard creep experiments at 650 °C / 800 MPa were performed. The results of the creep tests indicate that superimposed mechanical stresses during thermal exposure accelerate the degrading mechanism (Figure 6). For the pre-crept sample a significantly higher minimum creep rate, nearly one order of magnitude faster, compared to the unexposed state is found. The sample exposed at 670 °C without applied stress lies in between both curves, around half a magnitude slower than the pre-crept sample.

Figure 6: Creep behavior after exposing at 670 °C with and without applied stress in comparison to the reference. Both plots show, that the creep rate is highly accelerated by the assistance of mechanical stresses during thermal exposure.

Discussion

According to Cao [7] thermal exposure can possibly lead to two major changes in the microstructure of 718Plus. One is the formation and growth of TCP phases like η -phase and the other is the dissolution and coarsening of γ' -phase. For 718Plus it has been shown that, due to the chemical similarity between γ' -particles and η/δ -precipitates, transformation processes in 718Plus can take place as well [7,8,13]. According to observations of Löhnert et al. [8] this is possible by joining of γ' -particles building γ' -platelets, which transform to η -phase. This study confirms that this transformation doesn't seem to happen during long time thermal exposure below 680 °C. The size and area fraction of η -phase doesn't increase during thermal exposure. This is in good agreement to Xie et al. [13] who observed that the formation of η -phase is rather sluggish and the amount of η/δ -phase in 718Plus remains relatively stable during thermal exposure at 760 °C. Besides, no formation of other TCP phases has been detected subsequently to thermal exposure, which is consistent to other publications as well [7,14]. Secondly the dissolution and coarsening of γ' -particles can lead to a reduction of strength in the material. TEM investigations showed that the γ' -phase has coarsened slightly after exposure at 680 °C. Generally, the coarsening behavior of the γ' -phase in 718Plus is rather slow, which can be attributed most likely to the partition of Nb into the γ' -phase and the low effective diffusion coefficient [7,13]. In comparison, exposure of alloy 718 at 680 °C leads to significant coarsening and at 700 °C the γ' -phase increases nearly by one order of magnitude [30]. Since the coarsening behavior of γ' -phase is apparently relative slow the mechanical properties are only slightly affected by thermal exposure and remain relatively stable. The results of the tensile tests at room and elevated temperature show that the mechanical properties are improved after thermal exposure. One possible reason is that the performed γ' -hardening heat treatment steps lead to an underaged γ' -size and the optimum γ' -size is later on reached by thermal exposure. Only the elevated temperature test of the specimen exposed at highest test temperature of 680 °C shows reduced strength. Still this degradation in strength is low but it could be an indication that thermal exposure above this temperature could start to degrade the material more significantly. On the contrary the creep behavior is degraded and stronger affected by the performed thermal exposures. In agreement with observation by Cao [7] the early stage of creep is in particular affected and thereby the minimum creep rate is increased.

By evaluating the Norton-Plot, where the minimum creep rate is plotted versus the applied stress, a stress exponent n around 10 has been observed (Figure 7).

Figure 7: Norton Plot of reference and exposed material, respectively. The stress exponent n for the experiments is around 10.

For such high values of the creep exponent, dislocation mechanism like shearing of γ' -precipitates and Orowan bowing are presumably the dominant deformation mode. According to Unocic et al. [11] for 718Plus at stresses around 620 MPa and temperature of 691 °C shearing of γ' -particles could be observed. TEM analyses lead to the conclusion, that two deformation mechanisms are active. The dominant deformation modes are highly planar faulted structures on $\{111\}$ glide planes and additional coupled $a/2\langle 110 \rangle$ APB dislocation types could be found within γ' -particles. In general during the first stage of creep at this high stresses dislocation motion is strongly involved and the coarsening of γ' -phase lead to larger inter-particle distances and therefor higher creep rates [7]. Another possible reason for the decreasing creep strength could be the growth of the γ' -denuded zone surrounding η -particles. Those weak zones (see figure 8) have probably a stronger effect on the creep properties than on tensile strength, but further TEM investigations are necessary to confirm the detailed mechanism which causes the degradation of the creep resistance.

Figure 8: Apparent γ' -denuded zone surrounding the η -particle after exposing at 680 °C for 500h.

Summarizing the effect of thermal exposure on the mechanical properties, it can be stated that long term thermal exposure up to 680 °C doesn't degrade the alloy 718Plus to a large extent. The microstructure stays relatively stable. In contrary significant coarsening of the hardening phases occurs during exposure at 680 °C in alloy 718 which leads to a strong decrease in strength and creep resistance [31], which confirms the superior thermal stability of 718Plus.

On the other side applied stresses during thermal exposure seems to accelerate the degradation mechanism, increasing the minimum creep rate by nearly one order of magnitude. Yet the detailed mechanism causing this acceleration is unclear but further detailed TEM investigations on pre crept samples can clarify this.

Conclusion

The results show that a thermal exposure below 680 °C has no detrimental effect on the mechanical properties, which confirms the thermal capability of at least 680 °C. Also long term thermal exposure for 2000 h at 650 °C doesn't lead to reduction in strength and the creep properties aren't strongly affected. Metallographic examinations showed that the microstructure regarding grain size and η -phase stays stable in the temperature range below 680 °C. TEM investigations indicate a slight coarsening of the γ' -phase due to exposure at 680 °C. The strongest degradation could be observed for the creep resistance. Especially the minimum creep rate increases, possibly due to larger γ' -particle distances and the formation of a γ' -denuded zone. However, the reduction in creep resistance for thermal exposure without applied stress is not as significant as with applied stress. The results indicate that in the presence of stress the degrading mechanisms are accelerated and the creep resistance is stronger reduced.

Acknowledgements

The investigations in this paper are related to a comprehensive research programme on A718Plus conducted at RRD, with German funding by the Bundesministerium für Wirtschaft und Technologie (BMWi) under grant number 20T0813. The German Science Foundation (DFG) is also acknowledged for supporting the DFG graduate school 1229.

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