~~The~~ Effect of Aging on the Strength of ~~Newly Developed~~ Corrosion ~~Resistance~~ Resistant Incoloy Alloys 945 and 945X~~:~~ from ~~A~~a Microstructural Perspective

Author names

Affiliations

Corresponding author

Abstract

~~It has been found~~The results of this study show that Incoloy 945X ~~has~~is 19.36% ~~more hardness~~harder and 10.91% ~~more strength~~stronger than Incoloy 945. ~~The~~ Of particular interest is the morphology of precipitates ~~morphology~~ responsible for precipitation hardening in both alloys ~~is of particular interest in current investigation.~~. To identify and understand the physical ~~reason for this,~~mechanisms that lead to these results, we undertook an extensive microstructural study ~~is performed where~~in which γ' size, shape and elemental constitution ~~is~~was investigated and correlated to the aging conditions. ~~The~~ The main strengthening phase for both alloys is identified by transmission electron microscopy ~~studies reveal only one~~to be the main population of γ' precipitates ~~sized~~, which are between 10 and 25 nm ~~as the main strengthening phase for both alloys.~~in size. Scanning transmission electron microscopy line scans across the γ' precipitate ~~exhibit~~reveal more Nb and Ti deflection in Incoloy 945X than in Incoloy 945. This is further supported by the results of transmission electron microscopy ~~findings~~, in which γ' in 945X appear bright (because of Nb) with faceted growth, resulting in a higher value of 0.2% yield strength (1100 MPa) and hardness (430 HV5) than ~~the~~Incoloy 945. ~~Coarsening~~ For each aging temperature, the coarsening kinetics of the γ' phase ~~were~~was simulated ~~for each aging temperature~~by using JMatPro. ~~The coarsening simulations were found to be in good agreement~~, and the simulation results were consistent with the experimental results for the mean diameter of the γ' precipitates in each alloy.

Keywords: ~~945;~~ 945X; Scanning electron microscopy; Transmission electron microscopy; γ'; Coarsening simulations, precipitation, strengthening~~.~~

1. Introduction

The high-strength Incoloy alloy 945 was developed in 2008 by the Special Metals Corporation for the oil and gas industry~~, as it~~ and is more suitable than the traditional Inconel alloy 718 for deep-drilling applications ~~that involve deep drilling. This alloy~~. Incoloy 945 is a precipitation-hardened and corrosion ~~-~~resistant Ni-Fe-Cr alloy. Although ~~its~~ it contains less nickel ~~content~~ than Inconel 718 (53 wt%), this alloy provides excellent ductility, impact strength~~,~~ and resistance to stress corrosion cracking. In 2011, a higher~~-~~strength version of the alloy, called ~~the~~ "Incoloy ~~alloy 945X"~~945X" (54 wt% nickel content),

Commented [SC ED1]: The title of the manuscript should be concise and yet present the main research focus of the paper. We have therefore, revised it to make it impressive and informative for the readers.

Commented [EN QA2]: Although the journal does not have any specific instruction for punctuation in the title, I have removed it from the title and linked the texts through 'from a' for a better flow and clarity.

Commented [SC ED3]: Please mention the names of the authors who were involved in conducting this research. Please follow the below format for the names: First Author[1], Second Author[2]*, Third Author[3]

Commented [SC ED4]: Please provide full postal address of all the affiliations of the authors you have mentioned above. An example of the format is given below: [1]First Department, First University, Address, City, Country Name Also, mention the email address of each author, if available.

Commented [SC ED5]: Please provide the details of corresponding author from among the authors that you have listed above. The corresponding author will be the one who will communicate with the journal after submission, on behalf of remaining authors in the paper.

Commented [SC ED6]: The abstract reflects the aim of the study and the methods implemented to achieve the study's objectives. However, you may consider to provide a brief introduction about the phases discussed in the section, namely, γ' and γ'', that would help in conveying the essence of the study in a clear and well-defined manner.

Commented [EN QA7]: Precipitation hardening is a very common strengthening mechanism approached by scientists, especially for compositionally complex alloys. This area of research has been in limelight for quite some time. Hence, your statement here needs to be more intense in its expression of what exactly is the interest area of this paper. What new is the reader going to find in this paper?

Commented [SC ED8]: Space should be provided between the numeric quantities and their units. We have made the changes accordingly.

Commented [SC ED9]: Overall, we have edited this paragraph to improve the language and flow of content and present a more convincing summary of the study.

Commented [SC ED10]: We have deleted one of the keywords as it does not reflect the core research theme of the paper. It will also not make the paper promptly noticeable during online searches by researchers.

Commented [EN QA11]: I have added two more specific keywords that will reflect the core research theme of your paper. Please note that the journal allows to provide a maximum of 6 keywords. Currently, there is an extra keyword which needs to be deleted. Hence, you are advised to retain the ones that most convincingly presents your research findings.

Commented [SC ED12]: The Introduction section has detailed the research background related to his study in an elaborate manner. The importance of the various elements and phases in the alloy are clearly described. The abbreviation of the elements of the periodic table is not required and we have hence, removed them from the section.

Commented [EN QA13]: This is rather non-specific. Hence, I would suggest to provide the exact data here to present a comparative meaning to Inconel and reveal the superiority of the alloy.

was introduced. These Incoloy alloys can be used in high-pressure, high~~-~~-temperature ~~(HPHT)~~ applications~~,~~ and are approved for use under NACE MR0175/ISO 15156-3 up to levels V and VI [1].

As is normal with any ~~N~~nickel-based superalloy, the matrix consists of a face~~-~~-centred cubic (~~FCC)~~ fcc) structure called gamma (γ). The solid solution strengthening elements of ~~gamma~~γ are chromium, iron, molybdenum, titanium, aluminium~~,~~ and cobalt. The main strengthening precipitates, γ' ~~(~~Ni_3 (Al, Ti, Nb) and γ'' (Ni_3Nb) having $L1_2$ and DO_{22} crystal structures, respectively, and have been the subject of numerous investigations [2-7]. As reported by Hagel and Beattie [8], the γ' phase is coherent with the gamma matrix, with lattice (γ) misfits of 0.1 %, 0.5~~-~~% -1.0~~ %,~~% and greater than 1.25 % associated with ~~the~~ spherical particles, cubes~~,~~ and plates, respectively. The γ' phase is an A_3B phase, in which ~~the~~ element ~~substituting~~ A is Ni, ~~while~~whereas Co and B are replaced by Ti, Al~~,~~ and Nb. Hume-Rothery [9~~], [36,37~~-11] stated that Ni_3Al is the most stable γ' phase, followed by Ni_3Ti, Ni_3Nb~~,~~ and Ni_3Ta, in ~~the~~ order of decreasing stability.

A nickel content above 42 wt.% is typically required for resistance to aqueous stress corrosion cracking [~~10~~12]. Molybdenum and chromium in the alloy provide resistance to pitting corrosion in reducing acid and alkali solutions [~~11~~13,~~12~~14]. Niobium, titanium~~,~~ and aluminium are the primary precipitation~~-~~-strengthening components [~~13~~15]. Although titanium increases the strength and hardness of the alloy, an excessive amount of ~~it~~titanium is known to degrade the microstructural stability [~~14~~16]. Aluminium increases the volume fraction of the γ' phase [~~15~~17], which is expected to further increase hardness; however, a high aluminium content reduces the lattice mismatch~~/~~ and coherency strain, resulting in a net decrease in hardness. The metastable γ'' phase [5], [7], [~~16~~18-~~18~~20] has a body~~-~~-centred tetragonal structure ~~(BCT),~~ and usually precipitates at temperatures less than 650 °C. The nickel alloys normally ~~exhibit~~ undergoes γ'' precipitation ~~of γ''~~ under high coherency strain~~s~~ [~~13~~15]. ~~These are fine nano~~The precipitates are fine nanoparticles, like γ', with high hardening and strength, ~~having a~~and with length approximately six times greater than ~~their~~ width. This metastable phase tends to be replaced by a stable delta Ni_3Nb (δ) phase when exposed for extended periods to temperatures above 650 °C ~~for extended periods~~ [~~35~~21]. The presence of intergranular δ platelets [~~19~~22] with an orthorhombic crystal structure results in a loss of ~~hardness and~~ ductility [~~20~~23].

This study seeks to verify whether Incoloy ~~alloys~~ 945 and 945X ~~are known to~~ resist the formation of intergranular phases, ~~and this study seeks to verify this.~~as is suspected. This resistance could be due to a lower Nb content ~~of Nb~~ in the actual alloy composition ~~of the alloys~~, as compared ~~to~~with the Nb content in the parent alloy, Inconel 718. Typically, ~~the~~ nickel-based alloys have low carbon content ~~is low in Nickel-based alloys~~. Carbon tends to react with refractory elements to form MC-type carbides that reside at the grain boundaries and within grains, with the 'M' ~~mostly~~most often being Nb. Furthermore, Ti helps to form TiN; both the MC carbides and TiN ~~are beneficial for~~help

Commented [SC ED14]: We have replaced (Ni3Al, Ti, Nb) with Ni3(Al, Ti, Nb) to define the composition of the γ' phase in a clearer manner.

Commented [SC ED15]: We have replaced the old reference [9] with the article mentioned in the below comments box, wherever applicable. Please check if the intended modification is in line with your research perspective.

Commented [SC ED16]: You have used Hume-Rothery rules as a reference to infer the stability of Ni3Al phase as compared to Ni3Ti, Ni3Nb and Ni3Ta owing to the similarity in atomic radius of Al to Ni than the other mentioned elements. In this regard, it is more appropriate to substitute reference 9 with journal articles which present the Hume Rothery rules, namely,

W. Hume-Rothery, G. W. Mabbott, and K. M. Channel-Evans, "The freezing points, melting points, and solid solubility limits of the alloys of silver and copper with the elements of the B Sub-Groups", Philos. Trans. R. Soc. London, Ser. A. 233, 1934, 1-97.

Commented [EN QA17]: I suspect that the discussion here about various alloys and their main properties are a little extensive in comparison to the latter part of this paragraph that focusses on their precipitation properties. Hence, you can consider making this paragraph focussed and concise to retain the interest of the readers.

Commented [SC ED18]: We have edited the existing text as it was a little difficult to understand the context of this sentence. We have thus, slightly changed your meaning by removing the explicit reference to hardness which usually is known to improve the ductility.

strengthen the grain ~~boundary strengthening, inhibition of~~boundaries, inhibit grain growth and ~~reduction of~~reduce grain sliding, despite the~~ir~~ detrimental properties of reduced ductility and toughness. Few studies [~~21~~24,~~22~~25] have ~~been carried out~~focussed on 945 and the relatively new 945X alloys. The relationship between the microstructure and mechanical properties for these alloys ha~~ve~~s not been characterised as fully~~,~~ as ~~compared to~~has that of other ~~N~~nickel-based alloys. The aim of the current study is to investigate the microstructure of the 945 and 945X alloys under isothermal solution treatment and aging~~,~~ and analyse ~~their effects on~~how it affects the mechanical strength~~. The reason for which~~ of the alloy.

2. Experimental Methods

2.1. Experiment Materials

Incoloy alloys 945 (140 × 110 × 24 mm^3) and 945X (250 × 250 × 360 ~~mm), in its as received condition,~~mm^3) were supplied by Titanium Engineers, Inc and C. H. Robinson Europe BV, respectively~~.~~, and used as received. The ~~as received~~ alloys ~~presented~~had the microstructures of the type ~~of microstructure~~ typically used in oil and gas applications~~. The alloys in the as received condition~~ and were ~~termed~~ called 'as ~~'As Received'~~received' (AR) alloys~~ and details~~. Details of the AR heat treatment [~~14~~16] ~~are~~appear in Table ~~2~~1. ~~The~~ Table ~~1~~2 shows the results of ~~the~~ optical~~-~~ emission spectroscopy ~~(OES) studies carried out on~~applied to thin off-cuts from each alloy~~, are shown in Table 1~~.

Specimen	Alloy	Dimensions	Heat Treatment
ST	945/945X	14 ~~x~~ × 10 mm^2	1038 ~~º~~°C 1 h WQ
STA	945/945X	14 ~~x~~ × 10 mm^2	1038 °C 1 h WQ then 718 °C 8 h FC + 621 ~~º~~°C 8 h AC
AR	945/945X	14 ~~x~~ × 10 mm^2	1010-1066 °C for 0.5-4 h, WQ to RT 704-732 °C for 6-8 h, FC at 0.433-0.933 °C/min to 607-635 °C, then hold for 6-8 h, AC to RT
NS	945X	14 ~~x~~ × 10 mm^2	1250 °C 1 h WQ then 718 °C 8 h FC + 621 ~~º~~°C 8 h AC

~~The 945 and 945X alloys were subjected to thermal heat treatments under the conditions described in Table 2. The samples were ST in a preheated furnace to 1038 °C for 1 h and then quenched with water to RT 20 °C at a cooling rate of 50 °C/min. The ST samples were prepared for microstructural investigations, while the remaining samples were STA in a preheated furnace to 718 °C and aged at this temperature for 8 h~~.

Commented [SC ED19]: We have made contextual revisions here to provide a prompt link of scientific words to your research.

Commented [SC ED20]: We have edited and restructured this section at several instances to clearly demarcate clearly the various aspects of experimental approach of this study.

Commented [SC ED21]: It is important to understand the heat treatments and ageing cycles underwent by the as received samples because it plays a critical role in determining the significance of the study. As the experiments were conducted prior to the generations of results, it is essential to draft this section using the past tense. We have modified this section accordingly.

Commented [SC ED22]: Please note that Tables were not cited in order. We have renumbered the tables. Please check.

Commented [EN QA23]: I have edited the degree symbol here as journals expect it to be a symbol rather than a superscript "o".

Commented [SC ED24]: Table 2 clearly describes the sample nomenclature corresponding to the treatment subjected upon it. It is therefore not necessary to repeat the same content in the manuscript text. A sentence referring to the information presented in the Table would suffice. We have hence, deleted these extensive sentences from this section.

Note: Air cooling (AC); ~~W~~water quenched (WQ); ~~Furnace Cooling~~furnace cooling (FC); ~~Room Temperature~~room temperature (RT); solution treated (ST~~) Solution Treated;~~); solution treated and aged (STA~~) Solution Treated and Aged; Non~~); non-standard (NS)

Table ~~2~~1. Solution annealing and aging temperature of ~~the~~ 945 and 945X specimens.

Alloy	wt. % C	Si	Mn	Cr	Mo	Fe	Al	Cu	Nb	Ti	Ni
945	0.01	0.1	0.07	**20.5**	3.2	**22.2**	0.17	1.95	**3.11**	1.55	**47.04**
945X	0.01	0.08	0.04	**20.2**	3.2	**14.4**	0.15	2.09	**4.14**	1.57	**53.9**

Table ~~1~~2~~.~~. Elemental composition of as~~-~~–received 945 and 945X alloys.

[Other text deleted]

2.2. Microstructural studies

Metallographic samples for ~~light~~optical microscopy ~~(LM)~~ and scanning electron microscopy (SEM~~) –~~; XL30 ESEM with Oxford ISIS 310 EDX facilities~~ (~~, operated at 10 kV~~;~~, spot size 5~~;~~, working distance 5~~; Backscatter Electron~~, backscatter electron mode) were prepared by using standard mechanical polishing procedures. The specimens ~~to be observed~~ were ground by using silicon carbide papers with P240~~-~~–P2500 grit sizes and polished by using ~~the~~ abrasive cloths in ~~a~~ descending order of grit size~~s~~ from 6 ~~µm~~ to ~0.25 µm. Kalling's reagent etchant (100 ml HCl, 100 ml ethanol, 5 g $CuCl_2$) and colloidal silica (0.06 µm) were used to reveal the microstructure (i.e. the grain boundaries and metal carbides~~.~~). Transmission electron microscopy ~~studies were carried out~~was done with ~~the~~a JEOL 2100 operated at an acceleration~~g~~ voltage of 200 kV (beam current ~102 µA) with a spot size of 1 and an alpha angle of 2°. Thin foils prepared from each sample were mechanically ground ~~down~~ to ~~a thickness~~ less than 100 µm thick by using ~~the~~ silicon carbide papers (240~~-~~–1200 grit). ~~3 mm~~

Commented [SC ED25]: Even though the microstructural characterization has been conducted by sophisticated techniques, the manuscript lacks adequacy when reporting the mechanical properties of the alloy. Please enhance the clarity of this aspect by adding relevant statements in comparison to existing literature.

2.3. Mechanical Studies

To investigate the strength of the γ' precipitates, each sample was subjected to Vickers micro-hardness (HV) measurements ~~were carried out for each sample, using~~ done with a Rockwell Indentation Hardness Tester ~~by~~ (Tecquipment~~ ltd, to obtain insights on the strength of the γ' precipitates.~~, Ltd.). These measurements were ~~performed~~done by using a diamond pyramid indenter with a force of 5 kgf (HV5). The ~~set of~~ values were recorded while moving from one end of the sample to the other (~~unit:~~units of mm). ~~The~~ To prevent overlap of the strain fields, the distance between each indentation was ~~approximately >~~≳3*d*, where *d* is the indent diameter (in either ~~in~~the *x* or *y* direction~~), to prevent overlap~~

Commented [SC ED26]: The accurate application of a hardness testing requires careful preparation and performance. Please explain how you have ensured this aspect during your experimental procedure.

~~of the strain fields.~~). Tensile specimens from each alloy were machined ~~as per~~to the following dimensions: gage length ~~of~~ 22.5 mm, diameter ~~of~~ 6.35 mm~~,~~ and width of the grip section ~~of~~ 12.5 mm, with M8 threaded ends. The specimens were tested by using an Instron tensile machine at a standard displacement rate ~~(SDR)~~ of 2.22 ~~x~~ × 10^{-4}~~/~~ s^{-1}. SEM ~~with energy dispersive x-ray spectrometry (~~ EDS~~)~~ was ~~conducted~~used to determine the composition~~s~~ of the various phases~~. Scanning transmission electron microscopy (~~ and STEM~~)~~ was used to identify ~~and obtain~~ the chemical constituents of the ~~nano precipitates.~~nanoprecipitates. To simulate the precipitation kinetics of the γ' precipitate in the 945 and 945X alloys, ~~a~~ we used the JMatPro thermo-kinetic software package ~~known as JMatPro~~ (version 8.04) ~~was used;~~and compared the results from ~~the~~ simulation ~~and experiments were then compared. The~~with those from experiment. These simulations ~~helped provide~~provided insights ~~on~~into the size of the γ' precipitates ~~for~~, which could affect the mechanical properties of the alloy ~~could be affected~~.

~~2.~~3. Results and Discussion

3.1. Grain size after heat treatment~~s~~

~~Light~~ Optical microscopy images were obtained for the ST, STA~~,~~ and AR samples of each alloy. Fig~~.~~ure 1~~-~~(a) ~~is~~shows a typical image of alloys 945 and 945X, ~~containing~~which contain a γ matrix with grains and grain boundaries. ~~The nano scale~~In the subsequent sections, the nanoscale γ' phase in the γ matrix is examined for each alloy sample ~~in the subsequent sections~~. Initially, an uneven microstructure was obtained by swabbing the samples with a cotton bud containing ~~k~~Kalling's reagent (concentrated and dilute solutions); some grains were etched ~~while~~whereas others remain~~s~~ed under-etched with no clear distinction between ~~the~~ grain boundaries. By using colloidal silica (0.04 µm in size) as the final polishing suspension, the grains were not only polished, but also slightly etched, ~~thus~~thereby revealing the grain boundaries. Grain sizes were evaluated by using the intercept method~~, by~~ and considering 10 ~~light~~optical micrographs of each sample. No significant variation in ~~the~~ grain size ~~was observed, and an average grain size of 110 µm was recorded for~~ appeared, and each standard alloy specimen~~.~~ had an average grain size of 110 µm. However, due to ST at 1250 °C, the grain size in the 945X NS sample ~~had an~~ increased ~~grain size in the range of~~to 140~~-~~–150 µm, and exhibited an intergranular phase after double aging~~, as shown in~~ [see Fig. 1~~-~~(b)~~.~~)].

[Other text deleted]

The electron diffraction pattern (Fig. 6, left) for the 945 ST sample is more associated with a fcc γ lattice; however, due to the presence of small~~-sized~~ γ' precipitates, they are more coherent with the matrix and not easily distinguishable. In contrast, for the 945X ST sample (Fig. 6, right), upon higher magnification ~~((~~[Figs. 6(b) and 6(c)~~),~~)], the γ' precipitates ~~can be~~are clearly distinguished from the γ matrix. This is further ~~evident from~~supported by the electron diffraction spots ~~of~~from the γ matrix

Commented [EN QA27]: Although you have explained clearly about the intension to compare precipitation kinetics in both the alloys, this aspect requires further clarity as to how it adds to your research objective beyond just providing insights about the precipitate size.

Commented [SC ED28]: As per the journal guidelines, the results and discussion should be given in different sections. Consider revising this accordingly.

Commented [SC ED29]: Please mention the significance value obtained at this instance to help the readers analyze the difference in significance values obtained. This will also indicate the potential of your findings in comparison to existing literature.

and γ' precipitates. These very small precipitates give rise to secondary diffraction spots in the selected~~-~~–area diffraction patterns~~,~~ and are primarily associated with ~~the presence of~~ the γ' phase in the matrix.

Fig. 4. TEM images of 945 (left) and 945X (right) AR sample. Left: (a) Dark~~-~~–field imaging ~~–~~: Overview of γ' precipitates (~~appearing~~ bright) ~~which~~ spots) that are distributed homogeneously throughout ~~the~~ γ matrix with selected–area diffraction pattern ~~(SADP)~~ corresponding to ($\bar{1}10$) γ' phase. (b) Bright~~-~~–field mode showing ~~contrast image of γ' and γ matrix with~~ a faint line around precipitates distinguishing γ' precipitates from γ phase and (c) at a higher magnification, clearly showing γ' appearing black in a spherical shape a~~r~~bou~~nd~~t 4~~-~~–8 nm in diameter and in a compact~~-~~–disc ~~shaped ranging between~~shape about 10~~-~~–20 nm in diameter. Right: 945X AR: (a) shows ($0\bar{1}0$) γ' precipitates as grey precipitates in dark–field mode with ~~the~~ γ matrix appearing as dark grey. Panels (b) and (c) correspond~~s~~ to higher magnification, clearly showing γ' ~~in~~with spheroid shape (10~~-~~–15 nm) and coalescence of γ' into aggregates 10~~-~~–25 nm in size.

[Other text deleted]

Figure 7 shows the size distribution of γ' in the AR and STA samples ~~are presented in Fig. 7~~. The graph clearly indicates a peak position where the maximum number of γ' precipitates are found in any sample. The distribution is not a normal distribution, ~~as there are~~because some secondary peaks appear at 0~~-~~–5 ~~nm~~, 10~~-~~–15 ~~nm,~~ and 15~~-~~–20 nm for each alloy. The error bars associated with the distribution data ~~is~~are ±0.5 nm for each reading. The graph for the 945 AR and STA samples shows that the mean size ~~range~~ of γ' ~~is between~~ranges from 6~~-~~ to 8 nm, ~~while~~whereas that for the 945X AR and STA samples shows that the mean γ' size ~~range increases to~~ ranges from 10~~-~~ to 12 nm. ~~It is important to note~~Note that, for each alloy, the curves for the AR samples nearly overlap with the curves for the STA samples~~, for each alloy.~~. ~~It can be assumed that the AR samples of each alloy have undergone the same heat treatment as the STA samples~~. A mean size difference of ~4 nm between the 945 STA and 945X STA samples ~~was recorded~~is found for γ'. ~~It is important to consider here~~Note that ~~it~~this is not the mean, but the average γ' size of each alloy, which allows us to predict their cutting or bowing phenomena under service stress and cathodic protection.

[Other text deleted]

As discussed earlier, the amount of Nb ~~that is~~ present in 945 and 945X is a~~r~~bou~~nd~~t 3.11 wt% and 4.14 wt%, ~~as compared to~~which differs from its parent alloys Inconel 718 (5.06 wt%) and Incoloy 925 (0 wt%), respectively. This reduction in ~~the~~ Nb content ~~aids in resisting~~helps to resist the

Commented [EN QA30]: The figure legend is too extensive and does not give a clear idea about the main findings to be observed by the readers in the images. I have edited the legend for a concise and focussed presentation.

Commented [EN QA31]: You can mention this value in the image that corresponds to it. Also, please incorporate similar change for the dimension of compact disc.

Commented [SC ED32]: The journal instructs to keep text in the illustrations themselves to a minimum. Please consider to concise them by moving possible explanations to the text and retaining only the core points to express the main findings in the figure.

Commented [SC ED33]: The assumption made that the AR samples underwent the same heat treatment as the STA samples is misleading. We have hence deleted this statement.

precipitation of metastable γ'' (Ni_3Nb) and the stable δ phase. This change in chemistry results in the precipitation of only the γ' phase at the ~~nano scale,~~nanoscale and is evident from the TEM images in Fig. 4-1.6 (see section 3.3.1). ~~It~~This conclusion is further supported by the findings of Slama and Abdellaoui [~~24~~28], who reported that γ' appears before γ'' during isothermal aging at 680 °C. ~~The authors~~

Commented [SC ED34]: Please explain this notation. It is not clear to which figure you are referring.

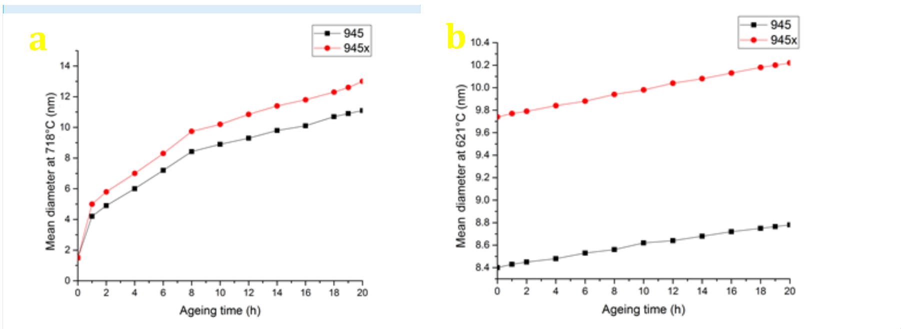
[Other text deleted]

~~t~~This increases further with the increase in ~~the~~ size of γ'. ~~In~~For the 945X samples, the γ' precipitates appear bright (Figs. 4 and 1.5), which could be attributed to the presence of higher-atomic-number elements ~~like~~such as Nb, which diffuse at the edges of the γ' precipitates to minimise the elastic strain caused by the lattice misfit between the γ' phase and γ matri~~x~~ces [~~28~~32,~~29~~33].

Commented [SC ED35]: Please clarify to what figure this refers.

[Figures and other text deleted]

The hardness values for the 945 and 945X ST samples are not surprising, ~~as~~since incomplete chemical ordering within the γ' precipitates and ~~a~~ small size contributes partially to the strength (see Fig. 10~~,~~; 330 ~~MPa~~ and 380 MPa, respectively) and hardness (140 ~~HV5~~ and 155 HV5, respectively) of the alloys. The solvus temperature of the γ' precipitates is less than the solution temperature of 1038 °C [~~23~~26], resulting in dissolution back into the γ matrix. The average hardness value for each sample ~~obtained~~ is mostly due to the presence of small ~~sized~~ γ' precipitates, which ~~are precipitated~~precipitate during ~~water quenching~~WQ, as shown in Fig. 4, and MC-type carbides and nitrides (NbC and TiN~~) that are precipitated)~~, which precipitate randomly throughout the structure, some of which dissolve into the γ matrix during solution treatment.



Commented [SC ED36]: The image panels should be in black colour. You can refer to the format in one of the published articles of this journal through the link https://www.sciencedirect.com/science/article/pii/S092150931931055X

c

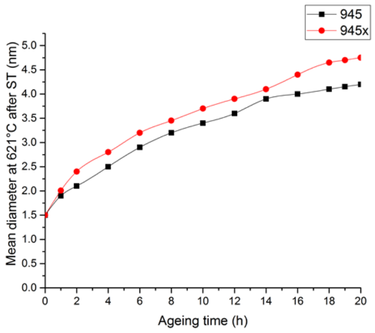


Fig. 10. Mean γ’ coarsening simulation of 945 (in black) and 945X (in red) STA samples ~~at~~for two -step aging ~~of~~at (a) 718 °C and (b) 621 °C. The simulation (c) shows the effect of aging at 621 °C on mean γ’ coarsening after solution treatment.

[Other text deleted]

The secondary aging at 621 °C helps to achieve clear edge definition by fractionally increasing the γ’ size, which enhances the hardness and 0.2% strength of the alloys. The effect of single and double aging on the morphology of γ’ in ATI 718Plus ~~has been~~was studied by using TEM ~~and reported in~~ [~~28~~32]. ~~It would be~~An interesting experiment would be to ~~carry out~~apply TEM again ~~on~~to both alloys~~,~~ ~~and~~ to see the individual effects of each aging temperature after solution treatment. The γ’ coarsening simulation shown in Fig. 11~~-~~(c) ~~demonstrates~~indicates the effect of individual aging at 621 °C for 8 h, showing an increase in ~~the~~ mean size of ~~the~~ γ’ particles to ~3 nm, which is contrary to the fractional increase of ~0.20 nm after consecutive double aging. The results of the theoretical simulations are close to the experimental ~~observations~~results (TEM) and could be used as a benchmark for comparison.

Commented [SC ED37]: There are more latest techniques/experimental approaches applied to alloys to study the effects on ageing temperature. Please consider providing a more convincing literary comparison based on online similar articles.

Commented [SC ED38]: The limitations of the study should be explained in short and focussed manner at the end of the ‘Discussion’ section. Please provide relevant information accordingly to retain the reader’s attention to your paper.

[Other text deleted]