Ultrasonic Velocity Measurements using MatLab for Monitoring Structural Health of Inconel 718

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***Abstract* — Evolution of the microstructure in Ni-based superalloys is critically controlled through optimization of various processing parameters such as Temperature, time, composition, degree of mechanical deformation etc. It is therefore very important to develop fundamental understating of the underlying mechanism and factors affecting such processes. In general, the choice of structural material for high temperature applications is primarily driven by application conditions. Inconel 718 alloy is widely considered as one of the candidate materials suitable for application at temperatures below 650ºC. However, for all practical purposes, it is rarely used for temperature greater than 560ºC. In addition, the component design should be optimum in order to maximize the life of the component. Inconel 718 being a precipitation strengthening material undergoes structural changes in terms of precipitate size in service, which may adversely affect the life of the component. Thus, it is highly imperative to periodically monitor the structural integrity of the component. It is well-known that crystallographic texture of the material affects the elastic and plastic properties of the component. Ultrasonic testing provides an alternative non-destructive method to determine elastic modulus, which is useful to assess the flaw present in the material. Any changes in elastic property owing to the exposure of component at elevated temperature affects the pulse transit time through a sample of given thickness. This variation in ultrasonic wave velocity through the sample is easily monitored by measuring Young's modulus. Consequently, ultrasonic testing is used as a Non-destructive testing (NDT) tool to monitor and characterize the structural integrity. In this study, MatLab is used to improve the accuracy in the measurement of ultrasonic velocity and a correlation is established between the microstructure and resultant ultrasonic velocity in Inconel 718 superalloy.**

Keywords--* *Superalloy; Ageing; Intermetallic Precipitation; Ultrasonic Velocity; MatLab

I. INTRODUCTION

The industrial demand for high temperature material with high structural stability has witnessed a phenomenal growth in the last two decades. One of the key requirements of high temperature applications is that its microstructure should be stable at application conditions. The development of contemporary high temperature materials is thus needed to enable the successful introduction of cleaner and more efficient next generation applications. Space Shuttle Main Engine (SSME) and gas turbines are applications which undergo rapid thermal cycles. The SSME is a liquid hydrogen-oxygen combustion engine and operates at temperatures ranging from -253°C to 750°C [1]. Ni-based superalloys are ideally suited for high temperature structural materials for such elevated temperature applications because they exhibit high mechanical strength and excellent resistance to surface degradation at elevated temperatures.

Superalloys are grouped into various categories. One such group is precipitation strengthened alloys that contains substantial amount of nickel, aluminum, and iron. These Ni-based superalloys are strengthened by precipitation of intermetallic in the form of γ', γ'', δ and MC. Precipitation hardening is produced in two steps: 1) solution treating and quenching the alloy to achieve supersaturated matrix, and 2) ageing at a lower temperature to produce nano-sized precipitates. The degree of strengthening resulting from the second phase particles depend on the distribution of particles in the matrix. γ' phase is the primary strengthening in Ni-based superalloys. It is composed of intermetallic phase enriched with Ni, Al and Ti. In γ'' phase, Ni and Nb combine in the presence of Fe as a catalyst to form Body Centered Tetragonal (BCT) Ni_3Nb. This phase provides high strength at low and intermediate temperature, but it is unstable above 923 K (650°C).

Inconel 718 (IN-718) is strengthened by γ''(Ni_3Nb). IN-718 also contains smaller quantities of Al and Ti which leads to the formation of γ' $Ni_3(Al,Ti)$ phase. In addition to these two phases, the extended service exposure at temperature in the range of 923 K-1023 K (650°C-750°C) results in the formation of stable orthorhombic delta δ phase formation. Further, carbides MC-type (M=Ti, Mo, V, Cb, Ta, Zr) type have been reported to precipitate at grain boundaries in IN-718 either during thermos-mechanical processing, heat treatment or in-service [2].

IN-718 is an alloy with many desirable mechanical properties such as high yield and ultimate tensile strength; good creep and rupture strength; and high resistance to fatigue. It also retains its strength and toughness when exposed to higher temperature for longer duration. It has relatively good corrosion and oxidation resistance at elevated temperature. It is most commonly used in gas turbine applications.

Depending upon application conditions, it is expected that intermetallic phase(s) will change which may adversely affect mechanical properties of the alloy. Any changes in constituent phase(s) may result in dimensional instability that will affect the performance of the component. It is very important to assess the structural integrity of the component and the evolution of crystallographic defects in the component. Since crystallographic defects affect the plastic and elastic properties of the material, it is equally important to monitor the materials health via ultrasonic method.

Damage identification is carried out in conjunction with five closely related disciplines that include Structural Health Monitoring (SHM), Condition Monitoring (CM), Non-Destructive Evaluation (NDE), Statistical Process Control (SPC) and Damage Prognosis (DP). There is a large number of Non-Destructive Evaluations (NDE), Non-Destructive Testing (NDT), and Non-Destructive Inspection (NDI) techniques for identifying local damage and detect incipient failure in critical structures. Quantitative NDE aims to detect and characterize microstructural properties as well as flaws in materials to predict performance and reliability of components. Two quantitative NDE approaches are now in use- "off-line" periodic inspection during scheduled outages and "on-line" monitoring during materials processing and in service. NDE is base discipline which helps in online monitoring for in situ structures such as jet planes, pressure vessels etc. to give prior knowledge of the damage location and also characterize the damage structure before its failure [3]. There is correlation between the microstructure of the material with its physical and mechanical properties (Figure 1). NDE is used as a non-destructive tool at low and affordable cost for non-intrusive investigation of the component at regular intervals during various stages in the manufacturing process by evaluating the microstructures.

During ultrasonic testing, following parameters are measured: variation in ultrasonic wave frequency, velocity, attenuation, backscatter amplitude, spectral analysis, and can perform acoustic microscopy. These parameters can be used to measure grain size, estimate the volume fraction of inclusions; calculate degree of recrystallization. In addition, ultrasonic testing can be used to determine mechanical properties such as elastic modulus, hardness, fracture toughness, strength of the structure, and monitoring Ductile Brittle Transition Temperature (DBTT). In general, change in ultrasonic velocity for a given alloy has been attributed to the variation in elastic modulus of the matrix caused by precipitation of various phases [4].

The aim of this study is to present recent trends of Ultrasonic Velocity measurement and correlate with microstructural evolution in IN-718 superalloy.

II. EXPERIMENTAL PROCEDURE

A. Heat Treatment

Table I, shows the chemical composition of the IN-718 alloy used in present study. The Time Temperature Transformation (TTT) diagram for IN -718 [5] is shown in Figure 2. The heat treatment cycle used for IN-718 was solution annealing at

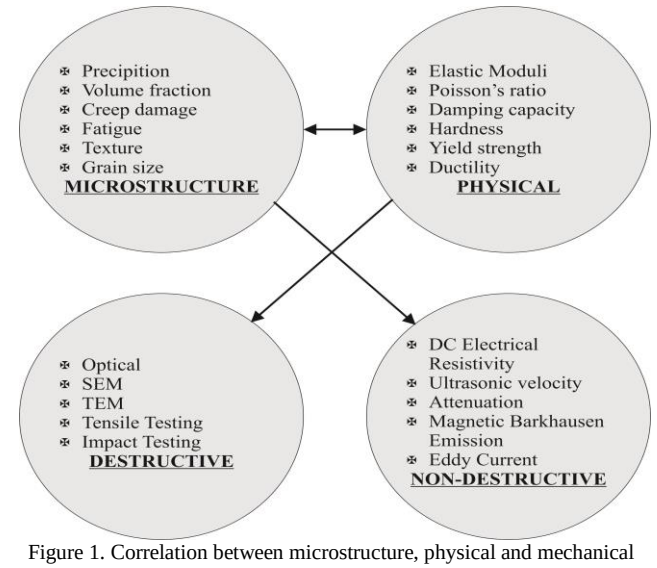

Figure 1. Correlation between microstructure, physical and mechanical properties of the material

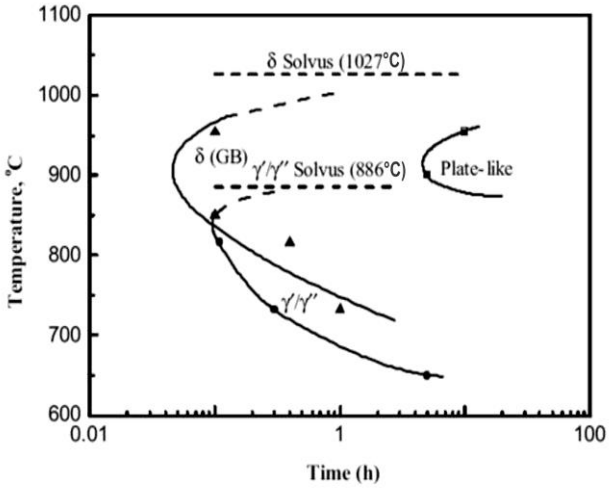

Figure 2. TTT diagram of Inconel 718

1253 K (980°C) for 1 hr, followed by water quenching to room temperature [6]. Subsequently, solutionized samples were aged at different temperatures and duration of time. Solution annealed (SA) specimens of dimension 25mm x 29mm x 10mm were aged and microstructural examination was performed.

Table I. Chemical Composition of Inconel 718

Element	%wt
Ni	53.30
Fe	17.66
Cr	19.21
Ti	1.03
Al	0.4
Nb	5.06
Mo	2.92
Co	0.01
C	0.04
Mn	<0.10

B. Ultrasonic Velocity measurement

Ultrasonic velocity (v) measurement involves determination of the distance travelled by the ultrasound and dividing it by time of travel between the first and second back surface echo, as shown in Eq. 1.

$$v = 2h / t \quad (1)$$

where, v = ultrasonic velocity, h = sample thickness and t = time of flight.

In case of in-situ applications, velocity ratio (longitudinal to shear) serves as a useful parameter as velocity ratio can be found out from time of travel data alone for longitudinal and shear waves. Some of the techniques used for velocity determination are pulse echo overlap technique, pulse superposition method, sing around method and phase comparison method.

The experimental setup used for Ultrasonic parameters measurement is shown in Figure 3. A 200 MHz broadband pulser-receiver and a 500 MHz digital oscilloscope were used for carrying out the ultrasonic measurements. For UV measurements, the RF signals were digitized and the gated back wall echoes from the oscilloscope were stored for further processing. Ultrasonic velocities were measured using 5 MHz longitudinal wave transducer. Longitudinal wave is affected by the elastic moduli, as mentioned in Eq. 2.

$$V_L = E (1 - \nu) / (1 + \nu) (1 - 2\nu) \quad (2)$$

Where, V_L = longitudinal wave velocity, E = Young's modulus and ν = Poisson's Ratio.

The accuracy of these measurements depends on the accuracy of measurement of time of flight and thickness of the specimen. For better accuracy and speed of measurement, a MatLab program is developed for calculating ultrasonic velocity and attenuation of the sample by reading the digitized RF signals and the gated back wall echo from the oscilloscope stored in the computer. A program for the same was also developed in LabVIEW software but it did not yield optimum results. Print screen of the MATLAB program is shown in Figure 4. Following are the steps in the program:

- At first, MatLab reads the excel file from the stored location in the computer.
- A graph (Figure 5.) for amplitude vs. time is plotted after removing first and last 100 values from the excel file containing 10,000 values of amplitude and time, in-order to remove noise echoes.
- After this while reading the excel file for a given sample, the program divides the file in two parts with the help of gating system in MATLAB.
- Subsequently, the program reads first 4000 readings of column A (amplitude values) and column B (time values) from the file and will find the maximum value of amplitude and time from first half.
- Then the program reads next 4000 readings of column A (amplitude values) and column B (time values) from the file and will find the maximum value of amplitude and time from second half.
- Variables will be assigned to both maximum values and the difference of these two values is then calculated.

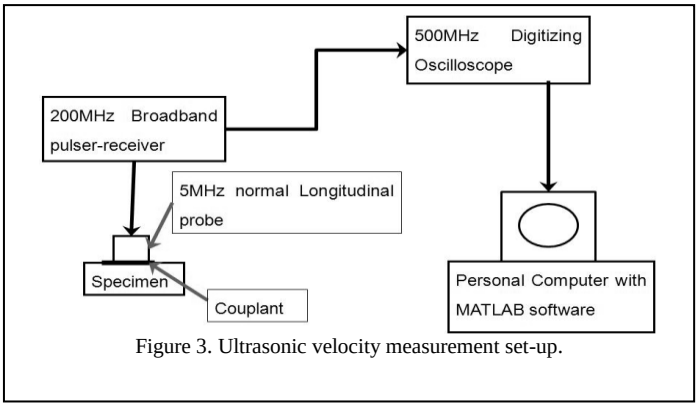

Figure 3. Ultrasonic velocity measurement set-up.

```
clc;
clear all;
close all;
format short g
y=xlsread('C:\Documents and Settings\Administrator\Desktop\1',1,'a1:a10000');
%read column1 from file
x=xlsread('C:\Documents and Settings\Administrator\Desktop\1',1,'B1:B10000');
%y=xlsread('C:\Documents and
Settings\Administrator\Desktop\exp1',1,'A1:A10000');   %read column1 from file
%x=xlsread('C:\Documents and
Settings\Administrator\Desktop\exp1',1,'B1:B10000'); %read column2 from file

r1_start=1000;%set limits start&end i.e. ignores initial and final noice
r1_end=8000;

r2_start=1000;
r2_end=8000;

d=input('Thickness of the sample=');

A=y(r1_start:r1_end,1);
B=x(r2_start:r2_end,1);
plot(B,A)
title('Echo Signals used for Calculating Ultrasonic Parameters')
xlabel('Time')
ylabel('Amplitude')

r11_start=1001;% find max value between two ends i.e. list of max. values in
1001-5000
r11_end=5000;
H_A1=y(r11_start:r11_end , 1);
H_A11=x(r11_start:r11_end,1);
[max11, ind11]= max(H_A1)
v=max11
v1=ind11
print_final1=H_A11(v1,1)

r22_start=5001; %find max value between two ends i.e. list of max. values in
5001-8000
r22_end=8000;
H_A2=y(r22_start:r22_end,1);
H_A22=x(r22_start:r22_end,1);
[max22, ind22]= max(H_A2)
i=max22
i1=ind22
print_final2=H_A22(i1,1)

h=print_final2-print_final1

t=2*d
UV=t/h

AT=20*log(v/i)/t
```

Figure 4. MATLAB program

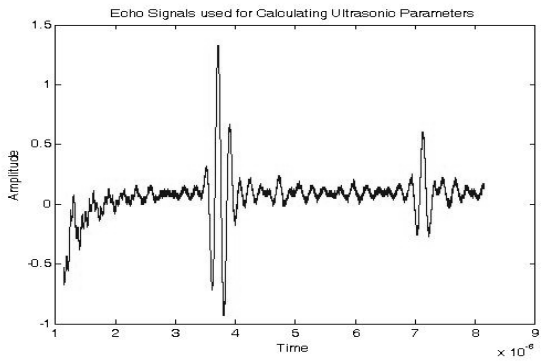

Figure 5. RF signal of Solution Annealed IN-718 specimen

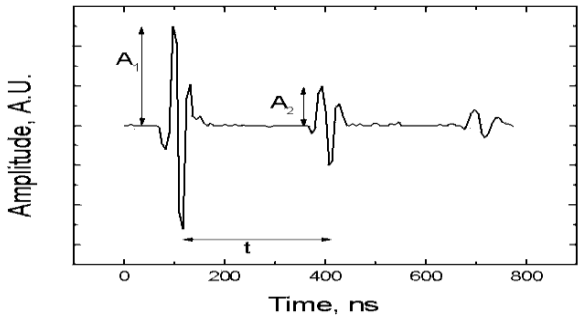

Figure 6. RF signal showing first and second back wall echo. (A_1 and A_2)

After calculating ultrasonic velocity, attenuation for the same specimen is calculated using formula:

$$Attenuation = \frac{20\ log\ \frac{A_1}{A_2}}{2xthickness\ of\ the\ specimen} \quad (4)$$

Here A_1 and A_2 is shown in figure 6.

III. RESULTS AND DISCUSSION

Considering potential sources of errors such as non-uniform heating in furnace, non-uniform quenching and inaccuracy in thickness measurement, the ultrasonic velocity and attenuation for heat treated IN-718 specimens were measured, by taking following precautions:

- Sample surface was polished before measurement to avoid scales.
- Front wall and back wall echoes of the sample were made parallel.
- Good quality industrial couplant was used.
- To avoid effect of localized variations, velocity was measured at 5 different locations of each sample and its average was considered as final velocity.
- Velocity measurement of all samples is performed in a stretch to avoid variation of pressure applied on the probe.

Information about microstructural induced changes in the elastic moduli can be deduced from the ultrasonic velocity by Eq. 5,

$$\mathbf{v = \sqrt{(c/\rho)}} \quad (5)$$

where v= ultrasonic velocity, c= elastic stiffness and ρ= density.

Table II shows the detailed description of the observation along with the variation in ultrasonic velocity data obtained manually and using MatLab program. Figure 7 to 11 shows the microstructure corresponding to the Solution annealing (SA) at 980°C, subsequent water quenching and the SA specimens thermally aged at 650°C (25 h) + 620°C (8 h) + AC; 750°C (75 h) + 620°C (8 h) + AC; 800°C (50 h) + 620°C (8 h) + AC and 900°C (100 h) + AC. Each specimen after heat treatment was mechanically polished and etched with a chemical solution consisting of 50% HCl, 10% HNO3, 2% HF and 38% of distilled water for optical and scanning electron microscopic (SEM) examination. The resulting microstructures are in accordance with the TTT diagram (Figure 2). Samples aged at 750 °C for 75 h showed extensive precipitation of γ' and γ" intermetallic phases. At 1173K (900 °C), it is expected from the TTT diagram that for longer time of exposure; nucleation of stable orthorhombic δ phase will start from γ". δ-phase degrade the strength of the alloy by consuming the precipitation strengthening elements. And this is one of the reasons for sudden change in Ultrasonic Velocity at 1173 K (900°C) for longer exposure time. In addition, there is a potential for the formation of MC type carbides at grain boundary, which may affect the ultrasonic velocity.

It is observed from Table II on correlating with the micrographs that ultrasonic velocity is influenced by the volume fraction, coherency, fineness and distribution of precipitates. Ultrasonic Velocity (UV) in a given metallic medium is attributed mainly to its structural features and characteristics. Attenuation of ultrasound gives rise to absorption and scattering of the beam in the metallic material during its propagation. These two characteristics adversely affect the UV i.e. to say velocity will decrease in presence of these characteristics. The analysis of result with reference to variation in the UV is given below:

1) In the unaged condition the velocity is minimum. Comparing with the microstructure it is evident that the equiaxed grains are very few in numbers and thus attenuation and scattering is expected to be of low degree. However the presence of intermetallic phases seems to have scattered the wave resulting in low velocity.
2) With reference to the microstructure in micrograph number 9 the velocity shows an increase in tendency. The aged structure consist of mainly γ' and γ" phases depending upon the ageing temperature and time. These micro-constituents present in the material after ageing treatment is so widespread and proportion is so imbalance that the attenuation and scattering behavior of the ultrasound can be considered to be negligible and hence there is substantial increase in the ultrasound.
3) However a critical comparison between the microstructures shows that there is just a marginal difference in UV which is mainly attributed to very low degree of difference in the micro-constituents.

IV. CONCLUSION

- Apart from the instrumental method of measuring the Ultrasonic Velocity in IN-718 alloy using RF signal a software based technique (MatLab) has also been used with the purpose of incorporating computational accuracy for the measurement.
- Ultrasound Velocity in age hardened alloy is found to be greater than the unaged hardened alloy.
- The range of ageing temperature and time selected has shown that there is a marginal difference in the micro-constituents after age hardening and therefore the Ultrasonic Velocity has the least significant variation in these cases.
- Ultrasonic Velocity measurement can further be expanded for measuring the Young's Modulus and other related properties of IN-718.

ACKNOWLEDGMENT

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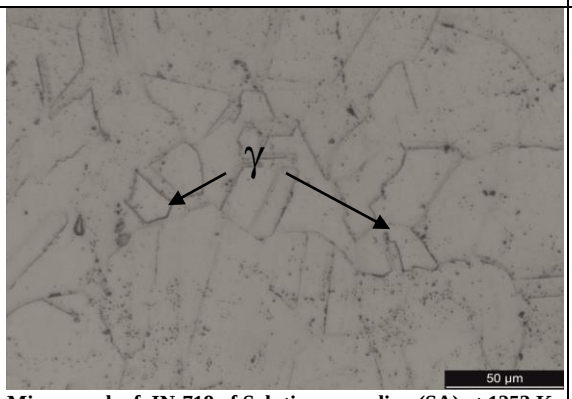
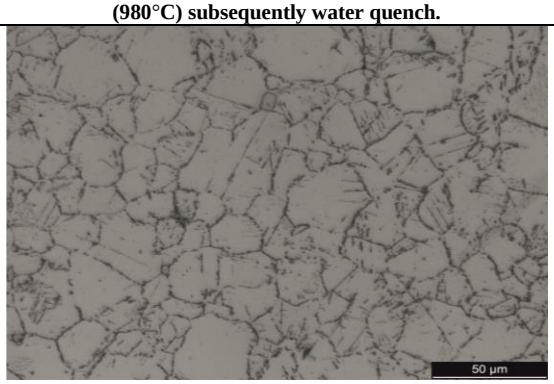
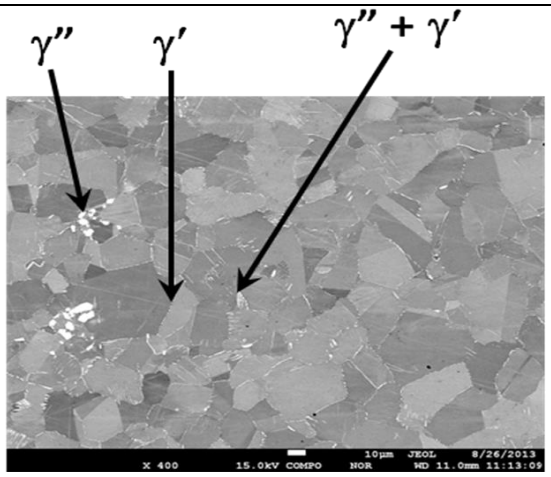
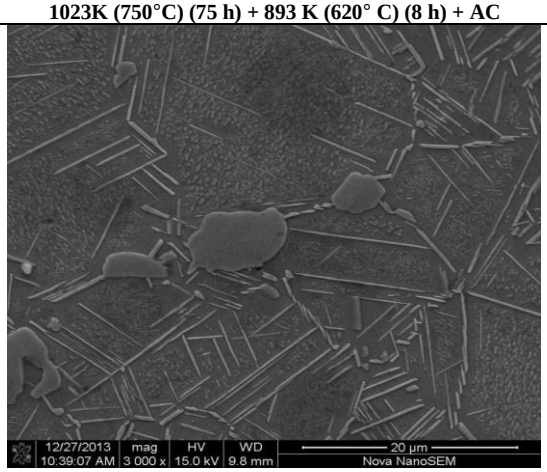
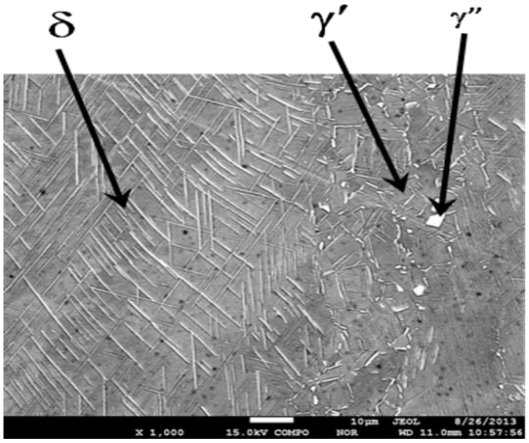
Table II. Detailed Observation

Fig. No.	Micrographs	Ageing Cycle	Descriptions	UV (Manual) (m/s)	UV (MatLab) (m/s)	Average UV (m/s)
7	 **Micrograph of IN-718 of Solution annealing (SA) at 1253 K (980°C) subsequently water quench.**	980°C for 1hr and then water quenched. (SA)	It shows almost equiaxed, homogenized austenitic grains. Some black particles mainly impurities or finely dispersed intermetallic phases seems to be present.	5789.0	5786.18	5787.59
8	 **Micrograph of IN-718 SA specimen thermally aged at 923K (650°C) (25 h) + 893 K (620°C) (8 h) + AC.**	SA + 650°C (25hrs) + 620°C (8hrs)	It shows relatively finer and coarser equiaxed austenitic grains with finely dispersed intermetallic phases and some impurities. The coarsening of grains seems to have taken place due to ageing at 650°C.	5812.0	5817.08	5814.54

9	 **Micrograph of IN-718, SA specimen thermally aged at 1023K (750°C) (75 h) + 893 K (620° C) (8 h) + AC**	SA + 750°C (75hrs) + 620°C (8hrs)	The thermally aged structure consists of coarse austenite grains with white regions showing the presence of γ'' as well as acicular γ'.	5823.8	5835.56	5829.68
10	 **Micrograph of IN-718, SA specimen thermally aged at 1073K (800°C) (50 h) + 893 K (620° C) (8 h) + AC**	SA + 800°C (50hrs) + 620°C (8hrs)	The structure predominantly consists of γ' and very low proportion of γ'' and δ phases due to ageing at 800°C.	5831.6	5829.48	5821.54
11	 **Micrograph of IN-718, SA specimen thermally aged at 1173K (900°C) (100 h) + AC**	SA + 900°C (100hrs)	Aged structure exhibits the δ-phase resulting from the dissolution and reprecipitation of γ' and γ''. It also shows the presence of both γ' and γ'' with varying proportion.	5818.2	5825.06	5821.63