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TOUGHNESS AS A FUNCTION OF THERMO-MECHANICAL PROCESSING AND HEAT TREATMENT IN 718PLUS® SUPERALLOY

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Abstract

ATI 718Plus® Alloy is a new cost-effective superalloy which fills the gap in temperature capability between 718 and Waspaloy nickel alloys. The effect of thermal mechanical processing and heat treatment on the room temperature impact toughness and fracture toughness of ATI 718Plus® Alloy has been evaluated. Fractography, microscopy and tensile testing were used to determine the microstrucutral features associated with high toughness. Impact toughness was measured with Charpy V-notch samples, while fracture toughness was determined using three point bend samples. The observed toughness was comparable to Alloy 718. Grain boundary delta phase was found to have the most significant influence on toughness where its presence had a net negative affect.

Background

For engine cases, one of the requirements is sufficient containment of shrapnel in the unlikely event of a rotating systems failure. Charpy V-notch tests give a high strain rate toughness measurement important in containment [1]. Three point bend testing is significantly slower and can be used to measure critical stress intensity factor. There has been extensive work on the toughness microstructure relationships in alloys such as Alloy 718 [2-5], Waspaloy[6] and others [7]. ATI 718Plus Alloy has little published information on the structure toughness relationship to date. Understanding the processing and toughness relationships in ATI 718Plus Alloy is important for adoption of this alloy in engine casing applications.

Experimental Procedure

<u>Design of Experiment</u>

Previous work has shown that forging temperature, pre-solution heat treatment, solution heat temperature and aging heat treatment have significant effects on microstructure [8,9]. In order to test the direct effects of thermo-mechanical processing variables and their interactions, a two level full-factorial design of experiments was used. Table 1 summarizes the factorial design. The thermo-mechanical processing used in the experiments was meant to simulate final part manufacturing.

Table 1: Factorial experimental summery.

Factor	Level 1	Level 2
Forging temperature	996°C	1038°C
Pre-solution treatment	Pre-solution treatment	No treatment
Solution temperature	954°C	982°C
Aging treatment	Standard age	Overage

Material originating from a single ingot of triple melt (VIM, ESR, VAR) ATI 718Plus Alloy was used. The ingot material was processed to 102 mm round bar using standard billet conversion practices. The chemistry of the ingot material, shown in table 2, is typical of ATI 718Plus Alloy. 10 sections of 114 mm length were cut from the 102 mm diameter bar.

Table 2: Chemistry of ATI 718Plus® Alloy used in experiments (wt%).

Ni	Co	Cr	Fe	Ti	Al	Nb	Mo	W
52.06	8.96	18.01	9.35	0.76	1.51	5.45	2.66	1.07

Processing:

These 114 mm long round bar sections were upset forged in two steps. For the final step of the two step forging, heated plates were used to reduce die chilling and to produce a more uniform structure. In order to test the microstructural differences that occur during forging, ten total pancake forgings were performed at either 996°C or 1038°C.

One pancake from each forging temperature was split in half. Two full pancakes and one half pancake from each forging temperature were given a pre-solution heat treatment. The pre-solution treatment was 871°C for 16hrs, a combination previously found to precipitate significant delta phase [10, 11].

Individual three point bend test blanks were cut from the split pancakes. Half of the test blanks (two of each condition above) and half of the pancakes (one pancake from each condition above) were given one of two solution heat treatments; one half were solution heat treated for one hour at 954°C while the other half were heat treated at 982°C for one hour.

Each of the 8 whole pancakes was split. One half of each pancake and half of the test blanks were aged in one of two ways. One half received a standard aging heat treatment to get an optimum gamma prime structure, while the other halves were given an over-age heat treatment. The specific heat treatments are shown in table 3.

Table 3: Aging heat treatments

Standard age:	**Overage:**
788°C x 8hrs Furnace cool at 56°C/hr 704°C x 8hrs, air cool	843°C x 2hrs Furnace cool at 111°C/hr 788°C x 8hrs Furnace cool at 56°C/hr 704°C x 8hrs, air cool

Testing

Tensile and three point bend samples were cut so that the gauge section was from the mid-radius of the pancake forging. Each of the 16 heat treatments discussed above were tested with one room temperature and one 704°C tensile test, one Charpy impact test and one three point bend test.

Tensile testing was performed at the ATI Allvac testing facility (Monroe, NC) per ASTM E-8. The ultimate tensile strength, yield strength, the sample elongation (4D), and reduction of area were recorded. Three point bend samples and Charpy V-notch were tested at Westmoreland Testing and Research (Youngstown, PA). Analysis of the toughness from crack-tip opening displacement in the three point bend geometry was performed using methods described in ASTM E1290-08.

Results

Microstructure

The aging treatment showed no changes at the length scales of light microscopy and therefore only the standard heat treatments are shown and discussed. The 996°C forge temperature yields a grain size of ASTM 11 while pancakes forged at 1038°C give an ASTM 9 grain size. In both cases, the grain size is stable with respect to the pre-solution, solution and aging heat treatments (row comparisons in Figures 1 and 2). Differences in grain size tend to obscure delta phase differences between the two forging temperatures. The colder forging has a larger area percentage of delta phase, the nature of the etching process could exaggerate this effect due to the finer grain size.

The pre-solutioning heat treatment resulted in more grain boundaries with delta phase present and more, larger delta fingers radiating from the grain boundaries. Delta phase increases are particularly visible when comparing the micrographs in Figures 1d and 2d. In Figure 1d there is very little delta phase along the grain boundaries where in Figure 2d (with pre-solution treatment) there is delta along the majority of grain boundaries as well as a number of perpendicular delta fingers growing.

The solution temperature significantly alters the delta phase content. The 954°C solution treatment shows higher delta phase fraction than the 982°C solution treatment. Darker etchings along the grain boundaries indicate more delta phase along the grain boundary. More and darker fingers are also seen in the lower solution temperature solution treated material (column comparisons in Figures 1 and 2).

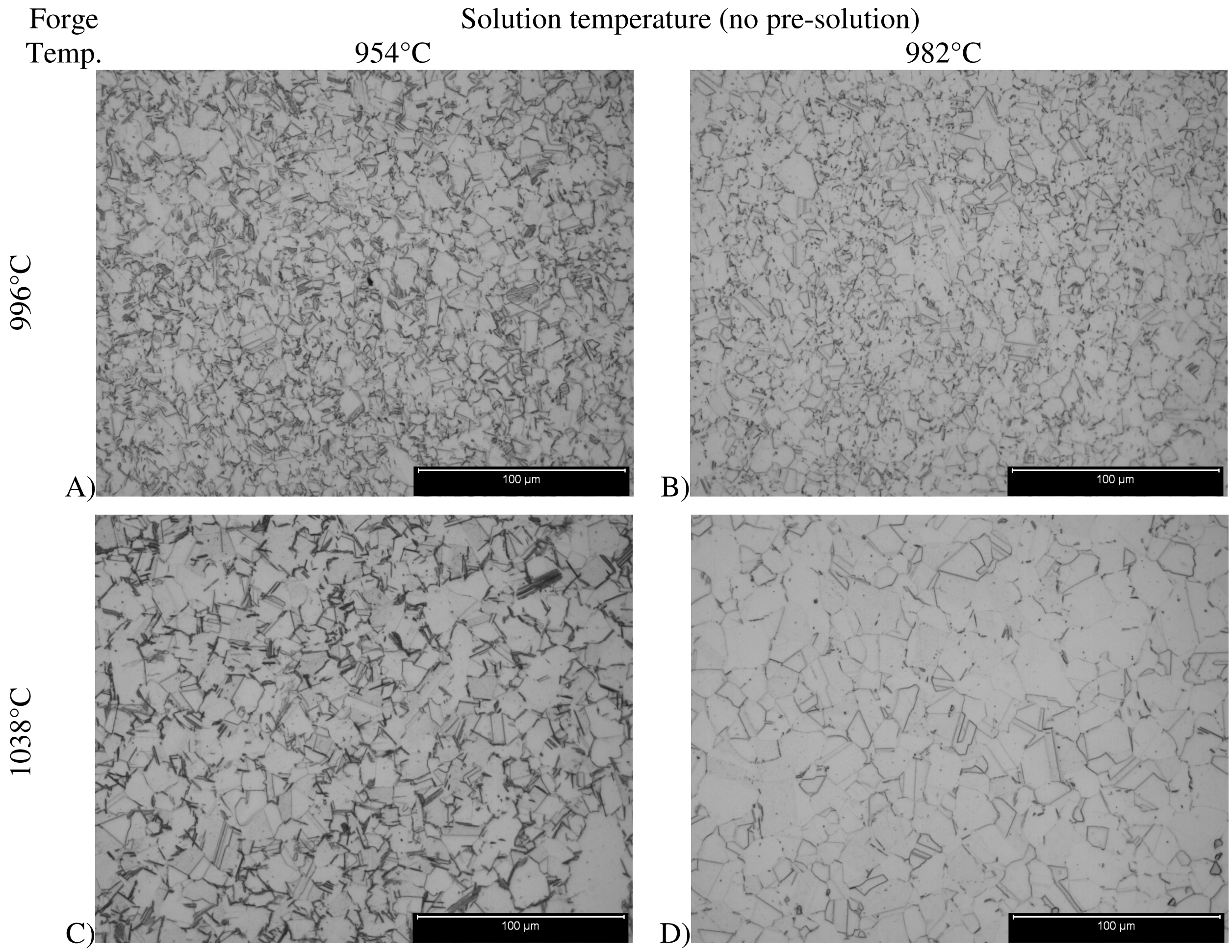

Figure 1: Showing the microstructures as a function of heat treatments for ATI 718Plus® samples with no pre-solution treatment.

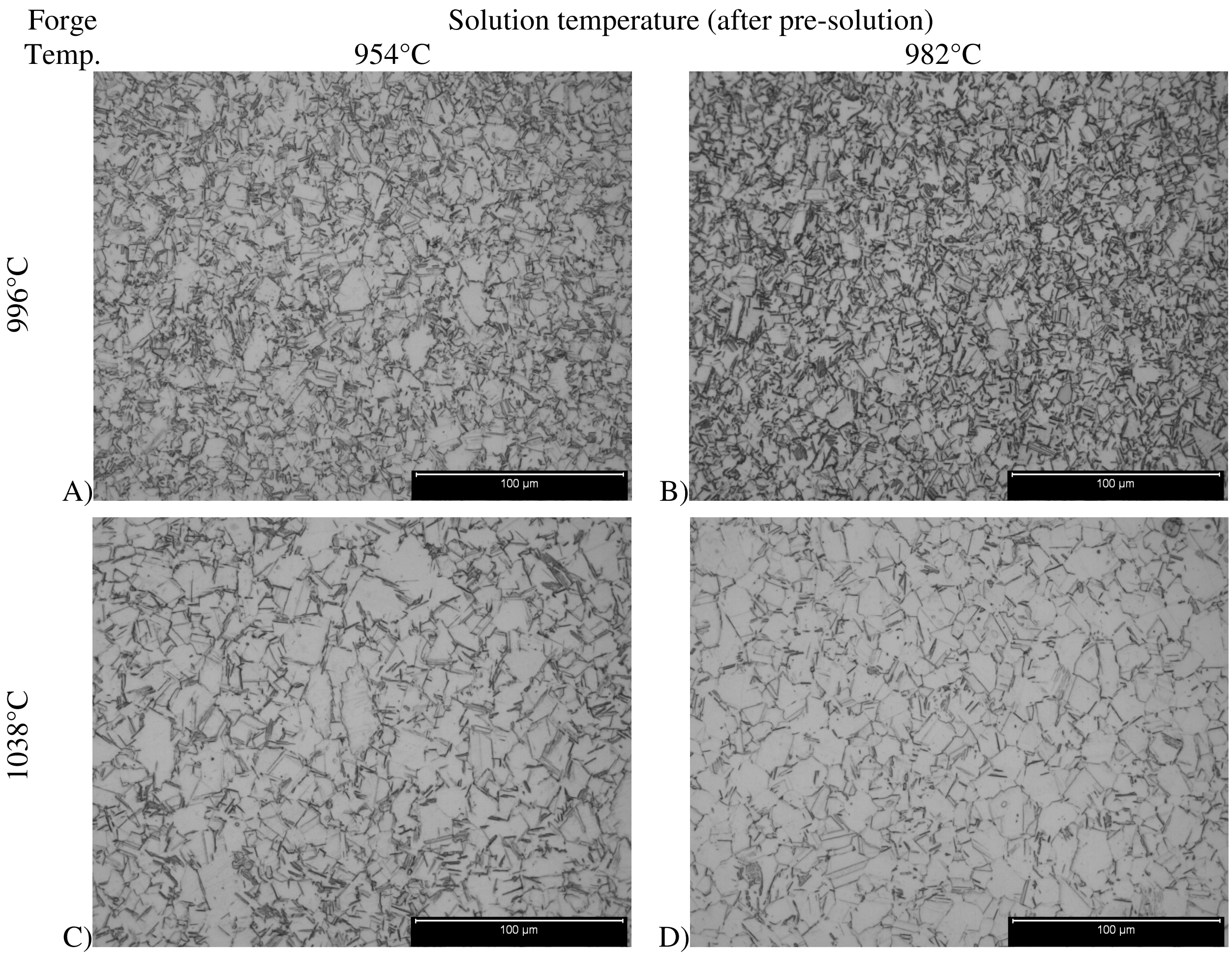

Figure 2: Showing the microstructures as a function of heat treatments for ATI 718Plus® samples with 871°C for 16 hours pre-solution treatment.

<u>Tensile Properties</u>

JMP (version 8.0.2, SAS Institute Inc.) statistical software was used to perform ANOVA analysis using the heat treatment as inputs and mechanical properties as the results. Full factorial analysis was run in all cases, and in all cases effects beyond the first order reduced the overall model fit. For this reason only the first order effects are discussed.

Strength: For room temperature strength (ultimate tensile strength is analyzed) three factors were statistically significant. The standard aging treatment was 23MPa stronger than the over-aged condition. The lower forging temperature (996°C) was 19MPa stronger on average, while the colder solution treatment (954°C) showed an average reduction in strength of 18MPa. The results for the tensile tests at 704°C were similar. The standard aging treatment showed a 31MPa improvement in strength, the colder solution treatment (954°C) reduced the strength by 14MPa and the pre-solution treatment reduced the strength by 13MPa. The main effects plots can be seen in Figure 3.

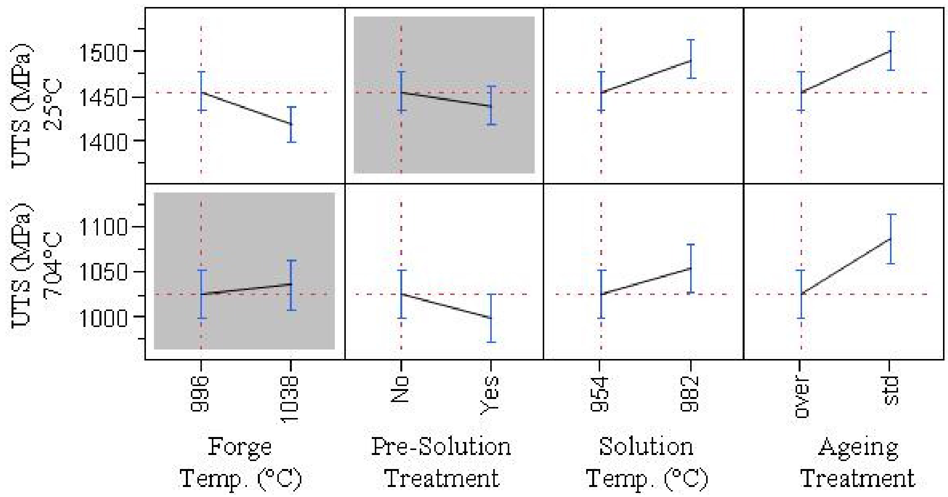

Figure 3: Main effects plots for room and 704°C strength (ultimate tensile strength) showing the statistical effect of each parameter (plots with gray background indicate that the factor did not have a statistically significant influence on the UTS).

Ductility: The pre-solution treatment and solution temperature were statistically significant factors in affecting room temperature ductility. Giving the material a pre-solution treatment improved the ductility by 4.4%, while the lower temperature solution treatment (954°C) reduced ductility by 4.1%. For the elevated temperature test, the effect of solution temperature was opposite from the room temperature results. The 954°C solution temperature improved the ductility by 11% compared to the 982°C solution temperature. The lower forge temperature (996°C) showed an improved ductility of 14%. The main effects plots can be seen in Figure 4.

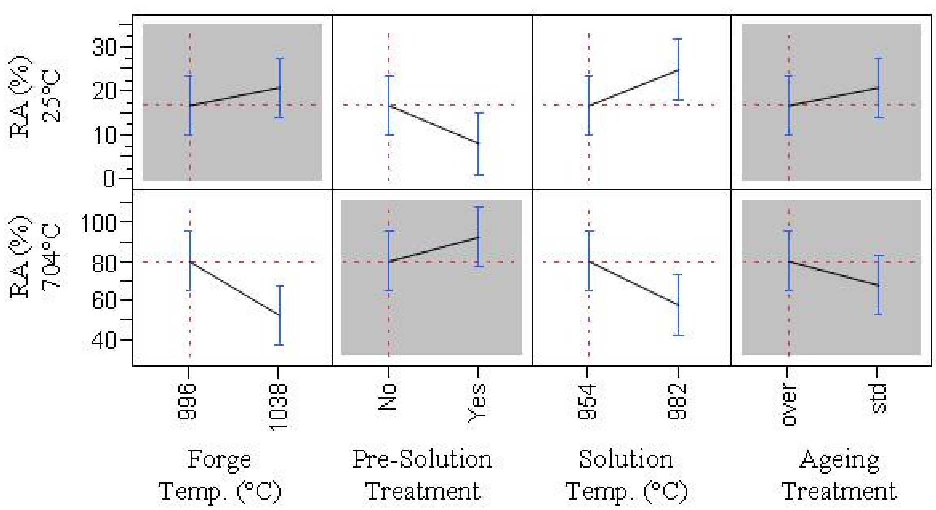

Figure 4: Main effects plots for room and 704°C ductility (reduction of area) showing the statistical effect of each parameter (plots with gray background indicate that the factor did not have a statistically significant influence on the ductility).

Toughness

A statistically significant correlation was found between the toughness (K) and the Charpy energy absorbed. Unlike tensile results such as yield stress and ultimate tensile stress, each of the toughness tests were independently run and are therefore examined separately.

In both of the toughness tests the three most significant predictors were the solution temperature, the forge temperature and the pre-solution treatment. These three factors also showed the same sign of effects with the highest toughness observed with 1038°C forging, no pre-solution treatment and a 982°C solution treatment. Each of these conditions shows around a 10% improvement in Charpy impact energy, and around a 7% improvement in fracture toughness. The biggest difference between the two tests was in the statistical effect of the heat treatment. In the Charpy test the effect of heat treatment was indistinguishable from the noise, while the three point bend test showed a significant 4% improvement in fracture toughness with the optimum heat treatment. The main effects plots can be seen in Figure 5.

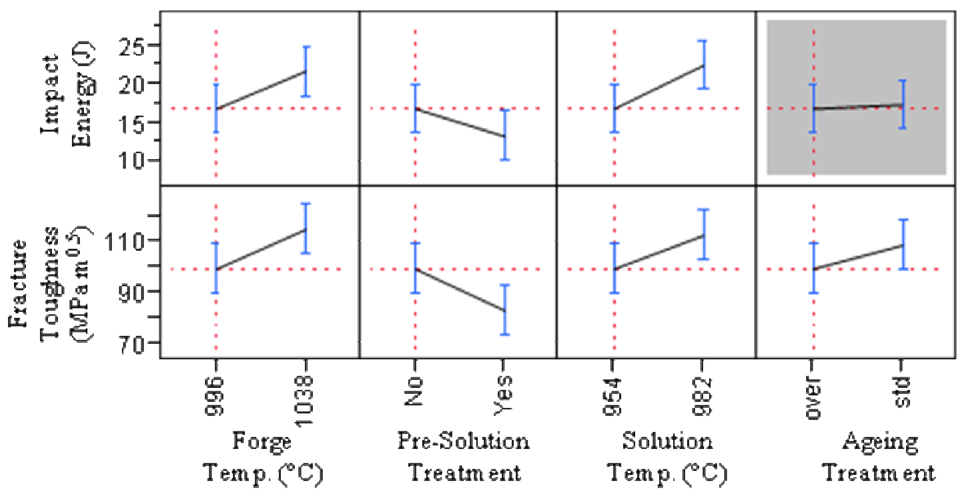

Figure 5: Main effect plots for the two measures of toughness showing the statistical effect of each parameter (plots with gray background indicate that the factor did not have a statistically significant influence on the impact energy).

Fracture surfaces

The three point bend fracture surfaces were examined using SEM. In all cases the fracture mode was trans-granular. This implies that there was not a dramatic change in fracture mode, and that all of the data can be discussed in terms of minor changes to a single fracture mode. A representative fracture surface can be seen in Figure 6.

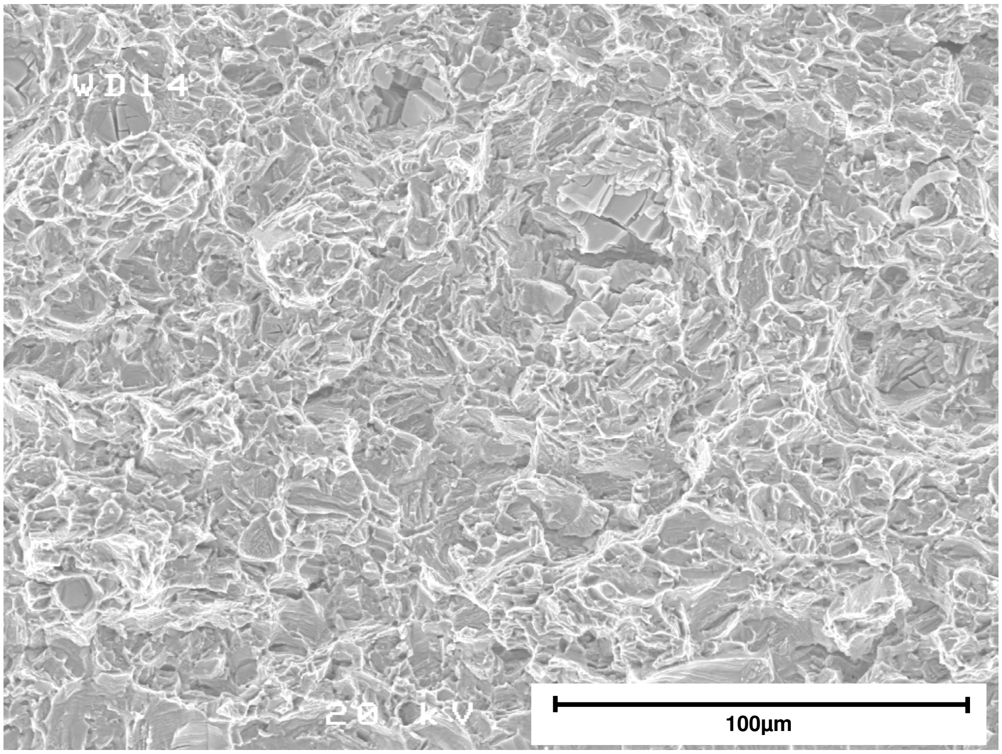

Figure 6: SEM image of a representative three point bend fracture surface (specific image is material forged at 1038°C, pre-solution heat treated, solution treated at 982°C and given a standard age heat treatment).

Discussion

Tensile Properties

The most significant predictor of strength in ATI 718Plus Alloy at both test temperatures is the aging treatment. This result is to be expected as the gamma prime is the primary strengthening and the standard heat treatment was developed in order to create a fine well dispersed gamma prime structure. The other factors that affect the 704°C tensile tests are those that directly alter the amount of delta phase observed (pre-solution treatment and solution temperature). The more delta phase observed, the lower the observed strength. This drop in strength is expected as the phase components (Al, Nb, Ti) are the same for delta phase as well as gamma prime pase. Therefore any increase in delta phase will come at the expense of the gamma prime phase fraction. At room temperature the forging temperature shows an effect which is most likely due to the finer grain size.

The aging treatment was statistically insignificant in changing the ductility at both room temperature and 704°C. At room temperature any of the heat treatment that increased delta phase reduced the ductility. The opposite trend is seen at 704°C, where heat treatments that increased delta phase improved the ductility. The high temperature results are consistent with the strength ductility tradeoff that is normally seen.

Toughness

The two measures of toughness are related, the Charpy impact sample measures both the energy of crack initiation and that of propagation, while the TPB samples are pre-cracked so the toughness is related only to crack propagation. Another significant difference is the timeframe of the cracking event, the TPB crosshead is moving 0.1in / min or slower, while in the Charpy impact arm is moving at more than 13,000in/min or 5 orders of magnitude faster. Slower speeds imply a slower crack propagation which in turn allows more time for dislocation movement and work strengthening which would lead to higher sensitivity to strengthening phases. The correlation between the Charpy and TPB tests still exists because in both cases the energy of the fracture is largely driven by the same mechanisms.

For both the three point bend and Charpy impact tests, the conditions which increased the delta content in ATI 718Plus Alloy led to lower toughness. Reduction in delta phase through hotter forge temperature, no pre-solution treatment, and a hotter solution temperature all improved the toughness. For the three point bend samples the aging treatment was also statistically significant, although the weakest factor in both magnitude and significance.

The tensile results tend to point to a fracture mechanism in the toughness samples. Strength showed little impact on the toughness while ductility was correlated with toughness. The ductility measurements show delta lowers ductility at room temperature which implies that delta is less able to accommodate strain than the surrounding matrix. Delta phase on the grain boundaries is more brittle at room temperature, and would therefore provide less resistance to crack growth. Toughness was only measured at room temperatures but these results indicate that at higher temperatures toughness might be improved by delta phase.

Conclusions

The themo-mechanical processing of ATI 718Plus® Alloy has a significant impact on the mechanical properties as well as the fracture toughness. These effects have been traced back to the microstructural phase balance created through the thermo-mechanical treatments.

- Delta phase precipitation on the grain boundaries improves high temperature ductility but reduces low temperature ductility.
- Strength is dominated by the aging treatment and is to a lesser extent affected by the amount of delta phase. If more delta phase is precipitated, then the volume fraction of the gamma prime phase is reduced and lower overall strength is present.
- Room temperature toughness can be altered by more than 30% through heat treatment. Delta phase is the primary driver of toughness and increasing delta phase is associated with lower fracture toughness at room temperature.

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