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APPLICATION OF DIRECT AGING TO ALLVAC® 718PLUS™ ALLOY FOR IMPROVED PERFORMANCE

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Abstract

Direct aging can result in significant improvement in mechanical properties of many wrought Ni-base superalloys. Its effectiveness is closely related to hot working and aging conditions and is also alloy-dependent. This process is most often used with γ" rather than γ' strengthening alloys.

Allvac® 718Plus™ alloy is predominantly a γ' strengthening alloy which shows excellent mechanical properties and high thermal stability up to 704°C in the solution treated and aged condition. It was uncertain if direct aging could be effective in this alloy. A test program was initiated to explore if direct aging could improve the alloy's performance and to determine the optimum process conditions. The variables evaluated included forging temperature, forging reduction, forging heating time and post-forging cooling rate. Mechanical tests and micro-structural study after different direct aging treatments demonstrated that direct aging is feasible at a production scale for alloy 718Plus and a significant improvement in performance can be achieved under well-controlled conditions. The mechanism responsible for such improvement is briefly discussed.

Introduction

It is well known that direct aging (DA), low temperature working followed by aging with no prior solution treatment, can significantly improve the mechanical properties of wrought Ni-base superalloys, especially strength and low cycle fatigue properties. This process has been tried in many wrought Ni-base superalloys, including alloys 718 [1–4], 625 [5, 6], X751 [7], IN783 [8] and others [9, 10]. Different degrees of success have been achieved.

It is evident from previous studies that processing conditions play a very important role in effectively applying direct aging to improve alloy performance, especially, the warm working conditions. Working temperature, reduction, forging heating and post-working cooling rate all must be controlled within the right range to maximize the effectiveness of direct aging.

The effect of direct aging also seems to be alloy-dependent. The most dramatic improvements were observed in Ni-base superalloys 718 and 625, which are strengthened predominantly by γ" phase. Direct aging can be effective in γ'strengthening Ni-base superalloys. However, results for these alloys were not as dramatic as for γ" strengthened alloys, and the effect was observed under very limited warm working conditions. For example, working at a temperature below the γ' solvus was necessary for effectively applying direct aging to superalloys such as Waspaloy and U720. This makes the process very difficult due to the poor workability of these alloys at such low working temperatures.

Alloy 718Plus™ is a newly developed Ni-base superalloy strengthened predominantly by γ' phase [11]. The chemistry and mechanical properties of this alloy have been introduced in a number of publications [12, 13]. Previous studies demonstrated that the processability of this alloy approaches that of alloy 718 and mechanical properties in the solution treated and aged (SA) condition, are comparable to Waspaloy up to 704°C, but with lower cost. It was of interest to determine if direct aging could be effectively applied to alloy 718Plus, potentially increasing its attractiveness for applications such as turbine engine disks. In addition to the question of how much properties could be raised, the optimum process conditions needed to be defined. The results of the program to address these questions are the subject of this paper.

Effectiveness of Direct Aging in Alloy 718Plus

Direct aging was first tried on alloy 718Plus by simply taking samples from standard hot worked mill product forms and applying the same two-step aging treatment used in the standard SA condition: 788°C x 2 hrs, furnace cool at 55°C/hr to 650°C and held 8 hrs at 650°C, air cool. The results, which compare SA to DA properties on products ranging from 19 mm bar to 300 mm billet, are summarized in Table I.

Table I. Comparison of Mechanical Properties for Solution Treated and Aged (SA) and Direct-Aged (DA) Alloy 718Plus™ Mill Products

Processing	ASTM Grain Size	HT*	Thermal Exposure	704°C Tensile				Stress Rupture at 704°C/ 552 MPa	
				UTS MPa	YS MPa	EL %	RA %	Life Hrs.	EL %
19 mm ϕ rolled Bar finished at 905°C (surface)	12	SA	None	1110	904	22.5	26.4	100	44.5
			760°C x 100 hrs	1067	873	37.8	47.3	87	41.4
		DA	None	1220	1072	15.1	16.4	261	40.4
			760°C x 100 hrs	1242	1098	13.2	12.2	386	26.6
200 mm ϕ forged Billet with starting forging temp. at 1010°C	8	SA	None	1118	899	16.2	16.8	356	42.6
		DA	None	1108	958	35.9	59.8	515	42.5
254 mm ϕ forged Billet with starting forging temp. at 1010°C	7	SA	None	1132	938	17.1	22.7	360	36.5
		DA	None	1089	900	33.4	52.7	500	35.5

*Heat Treatment:

SA: Solution (954°C x 1 hr., AC) + Aging (788°C x 2 hrs., 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)

DA: Direct Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)

It can be seen from Table I that a significant effect of direct aging was observed in some cases such as small size bar rolled at low temperature. Compared to the SA condition, both strength and rupture resistance were remarkably improved, and this improvement was not significantly diminished even after long-term thermal exposure. For the billet products, a strength increase occurred in the smaller size and a loss in the larger. These results clearly demonstrate that direct aging can significantly improve the mechanical properties of alloy 718Plus, but the processing conditions will be critical. The increase in rupture life for all of these samples also was especially interesting and worthy of further study.

Experimental Procedures

An experimental program using forged pancakes was planned to explore the relationship between forging practice and response to direct aging. Test material used in the trial was taken from 200 mm ϕ forging billet made from a triple melted, 500 mm production heat 609J-2. Chemistry of this heat is listed in Table II.

Table II. Chemistry in wt%, Heat 609J, Ingot 2 Used in Forging Trial

C	Cr	Fe	Co	Mo	W	Nb	Al	Ti	S	P	B
0.02	18.1	9.47	9.31	2.68	0.98	5.47	1.39	0.74	0.0004	0.013	0.004

A series of 50 mm cubes were cut from the mid-radius location of as-forged billet. Four groups of forging trials were conducted to evaluate the effect of forging temperature, forging reduction, heating time and post-forging cooling rate. Five forging temperatures (927°C, 954°C, 982°C, 1038°C and 1093°C) were selected for these trials, covering a wide range of usable forging temperatures for this alloy. Cubes were press-forged to 25 mm thick pancakes in three steps with upset reductions 25%, 34% and 50%, respectively. For higher forging temperatures (1038°C and 1093°C), all steps of forging were conducted at the designated temperatures, but for lower forging temperatures, the first and second steps were conducted at 990°C and the last step at the designated temperatures. Re-heating between steps was for 30 minutes. To reduce the effect of die chilling, alloy U720 plates were fixtured to the top and bottom of the cubes for both heating and forging. Still air cooling was used after the last step of forging except for the trial evaluating post forging cooling rates.

The effect of forging reduction in the finishing step was examined at forging temperatures of 954°C and 982°C. Nominal finish forge reductions of 20%, 50% and 70% were the goal. Other than forging reduction, the forge practice was identical to that of the temperature trial.

Since heating times for production forging operations could easily exceed 30 minutes, a three-hour heating time was employed as a variable in one experiment from forging temperatures of 927°C and 954°C. Hold time could have a significant effect due to the possibility of δ phase precipitation at these temperatures

Rapid cooling following hot working, such as water quenching, is often used in production to maximize the effectiveness of direct aging. However, large components will result in slower cooling rates. The effect of two cooling rates were examined at forging temperatures 954°C and 982°C, while the forging reduction and forging heating time were kept at 50% and 30 minutes, respectively.

An exploratory trial was conducted to see if cold working on as-hot worked material could synergistically work with direct aging to further strengthen this alloy. A single 704°C tensile test was performed on a sample cut from a pancake forged at 996°C, then cold rolled 20% reduction in thickness and direct aged. No difficulties were encountered in any of the forging or cold working operations.

Sample blanks were cut from the mid-radius location of the pancakes and given the direct age treatment. In some cases, half of the blanks from the same pancake were subjected to solution-age treatment (SA), consisting of 954°C x 1 hr, air cool + 788°C x 2 hrs, furnace cool at 55°C/hr to 650°C, held 8 hrs at 650°C and air cool. The same age cycle was performed on as-forged pancakes for direct aging. Tensile testing was performed at room temperature (in some cases) and 704°C. Stress rupture testing at 704°C / 552 MPa was performed on all forged samples.

Microstructures of broken test samples from all test conditions were examined by using optical and scanning electron microscopes (OP and SEM). Transmission electron microscope (TEM) analysis was conducted on direct aged samples at selected forging conditions to gain some understanding of the mechanism of the observed behavior.

Experimental Results

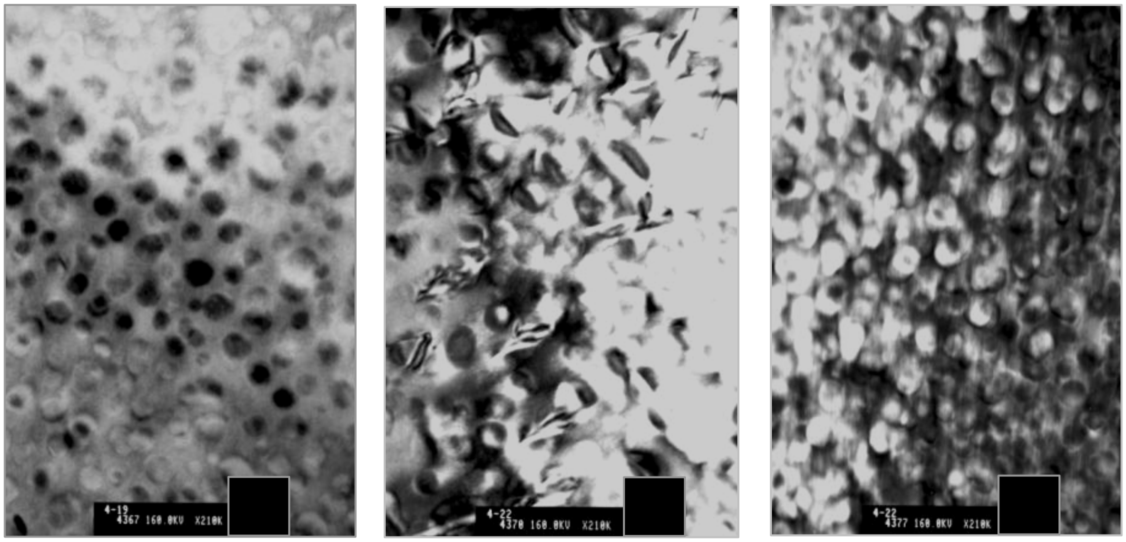
Table III lists the mechanical properties of materials subjected to solution-age and direct age treatments, forged at different temperatures. It can be seen that the maximum effect of direct aging occurred within a forging temperature from 954°C to 1038°C. For these conditions, there was a significant increase in yield strength and an improvement in stress rupture life. No improvement in strength was seen at the highest forging temperature (1093°C), and a notch break occurred in the stress rupture test from the direct aged sample. Grain size became finer with decreasing forging temperature, and there is the expected correlation with decreasing rupture life for both the SA and DA conditions. Extensive δ phase precipitation occurred at forging temperatures 954°C and 927°C but no noticeable δ phase formation was seen at 982°C or higher. While 982°C is actually below the δ phase solvus temperature of about 1010°C [13], it is most likely that lack of precipitation was due to slow kinetics of δ phase precipitation at this temperature.

Table III. Effect of Forging Temperature on Effectiveness of Direct Aging Alloy 718Plus™

Finishing Forging	ASTM Grain Size	HT*	704°C Tensile				Stress Rupture 704°C/552 MPa	
			UTS MPa	YS MPa	EL %	RA %	Life hrs	EL %
1093°C x 30 min, 50% Reduction	5	SA	1158	838	21.1	28.6	346	39.5
		DA	1056	850	10.7	13.5	0.6	N.B.
1038°C x 30 min, 50% Reduction	6	SA	1093	824	19.1	19.0	244	49.0
		DA	1100	879	12.0	16.7	447	31.8
982°C x 30 min, 50% Reduction	10	SA	1123	929	21.7	26.6	117	34.1
		DA	1172	973	16.4	40.9	157	36.2
954°C x 30 min, 50% Reduction	12	SA	1118	973	27.5	36.0	109	36.2
		DA	1205	1072	29.9	35.1	123	41.9
927°C x 30 min, 50% Reduction	Finer than ASTM 12	SA	1144	996	22.5	31.0	72	43.4
		DA	1203	1075	16.5	21.0	69	35.1

*Heat Treatment:
SA - Solution (954°C x 1 hr, AC) + Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)
DA - Direct Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)

Transmission electron microscope (TEM) structures of materials subjected to solution-age and direct age treatments are shown in Figure 1. Dislocations were clearly seen in direct aged material forged at 954°C, Figure 1(b), but none were observed in solution-aged material, Figure 1(a). The sizes of precipitates in both conditions are quite similar although the density of precipitates seems higher in direct aged material. The microstructure of the sample forged at high temperature (1038°C), Figure 1(c), was similar to that of solution-aged material.



(a) (b) (c)

Figure 1. TEM Structures of Alloy 718Plus™, (a) SA and (b) DA both Forged at 982°C, and (c) DA Forged at 1038°C.

The effect of forging reduction on the effectiveness of direct aging is presented in Table IV. It can be seen from these data that large reductions are not necessary to achieve the advantages of direct aging. Reductions of 12% to 20% gave a balance of room and elevated temperature tensile strengths and rupture lives that were equal to or better than the results of 50% to 67% reductions.

Table IV. Effect of Forging Reduction on Effectiveness of Direct Aging Alloy 718Plus™

Finishing Forging	Finish Forge Reduc-tion	HT*	R.T. Tensile				704°C Tensile				Stress Rupture 704°C/ 552 MPa	
			UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life hrs	EL %
982°C x 30 min.	20%	DA	1607	1299	18.2	23.7	1227	1102	24.5	54.1	166	34.4
	50%	DA	1576	1257	20.3	25.7	1172	973	16.4	40.9	157	36.2
	67%	DA	1539	1184	22.5	34.5	1164	943	17.6	20.2	178	53.4
954°C x 30 min.	12%	DA	1540	1223	21.6	26.1	1184	1036	17.5	16.8	245	31.4
	50%	DA	1600	1310	19.6	21.6	1205	1072	29.9	35.1	123	41.9
	67%	DA	1572	1246	22.1	27.3	1191	1013	19.0	20.3	141	34.0

*Heat Treatment:
DA - Direct Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)

Table V lists the test results of the effect of forge heating time. Extended heating times in the temperature range where δ phase can rapidly precipitate reduced both yield strength and stress rupture life significantly. There also appears to be a slightly negative effect on SA properties.

The effect of post-forging cooling rate on the effectiveness of direct aging can be seen in Table VI. It seems that the slower cooling did reduce the effect of direct aging on both tensile and rupture strengths, but the reduction was minor within the range studied.

Table V. Effect of Forging Heating Time on Effectiveness of Direct Aging

Finishing Forging Temperature	Heating Time	HT*	704°C Tensile				Stress Rupture 704°C/554 MPa	
			UTS MPa	YS MPa	EL %	RA %	Life hrs	EL %
954°C 50% Reduction	0.5 hrs	SA	1118	973	27.5	36.0	109	36.2
		DA	1205	1072	29.9	35.1	123	41.9
	3 hrs	SA	1130	950	18.3	23.8	71	43.4
		DA	1174	1047	36.2	70.0	55	39.9
927°C 50% Reduction	0.5 hrs	SA	1144	996	22.5	31.0	72	43.4
		DA	1205	1072	16.5	21.0	69	35.1
	3 hrs	SA	1126	1002	28.9	58.0	65	36.2
		DA	1162	1047	26.7	60.0	60	29.2

*Heat Treatment:
SA - Solution (954°C x 1 hr, AC) + Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)
DA - Direct Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650CF x 8 hrs, AC)

Table VI. Effect of Post-Forging Cooling Rate on Effectiveness of Direct Aging Alloy 718Plus™

Finishing Forging	Cooling Rate* °C/min	HT **	Room Temperature Tensile				704°C Tensile				Stress Rupture 704°C/ 552 MPa	
			UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %	Life hrs	EL %
982°C x 30 min, 50% Reduction	112	DA	1576	1257	20.3	25.7	1172	973	16.4	40.9	157	36.2
	42	DA	1552	1217	21.2	32.0	1168	980	22.4	29.4	146	45.7
954°C x 30 min, 50% Reduction	112	DA	1600	1310	19.6	21.6	1205	1072	29.9	35.1	123	41.9
	42	DA	1598	1298	19.0	25.8	1175	1007	23.0	39.0	99	42.5

* Cooling rate was the average rate from forging temperature to 760°C
** Heat Treatment: DA - Direct Aging (788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC)

Table VII compares the 704°C tensile properties of solution treated and aged, direct aged and cold worked + direct aged (CW+DA) material. It is obvious that cold working, combined with direct aging significantly increased the strength of alloy 718Plus.

Table VII. Effect of Cold Rolling + Direct Aging on Tensile Properties of Alloy 718Plus™

Finishing Forging	HT*	704°C Tensile			
		UTS (MPa)	YS (MPa)	EL (%)	RA (%)
982°C x 30 min, 50% Reduction	SA	1102	923	16.4	23.4
982°C x 30 min, 50% Reduction	DA	1156	989	15.1	21.9
996°C x 30 min, 50% Reduction	CW + DA	1328	1183	12.7	13.4

*Heat Treatment:
SA – 843°C x 8 hrs + 954°C X 1 hr, AC + 788°C x 2 hrs, 55°C/hr Cool to 650°C, 650°C x 8 hrs, AC
DA – 788°C x 2 hrs, 55°C/hr cool to 650°C, 650°C x 8 hrs, AC
CW+DA – 20% Cold Rolled + 788°C x 2 hrs, 55°C/hr Cool to 650°C, 650°C x 8 hrs, AC

Discussion

The results of this study clearly demonstrated that direct aging can very effectively improve the strength and stress rupture resistance of alloy 718Plus. Considering the fine grain size and high strength resulting from direct aging, the low cycle fatigue resistance of this alloy should also be significantly improved although further experimental verification is necessary. In contrast with previous studies on alloy 718 where the creep or stress rupture properties were normally unchanged, direct aging can significantly improve rupture properties of alloy 718Plus. DA processing of this alloy is also different from Waspaloy in that hot working at temperatures above the γ' solvus can achieve a good, direct age response.

Among the process parameters studied, forging temperature appears to be the most critical.. The optimum temperature range for DA processing alloy 718Plus appears to be from about 954°C to 1038°C. Figure 2 shows the response to DA processing as the increase in DA over SA properties, as a function of forging temperature. It is obvious from this figure that the forging temperature dependencies of strength and of rupture life are different. As expected, yield strength increasesd with decreasing forging temperature. The smaller increase at the lowest forging temperature was probably due to adiabatic heating. There was almost no change in rupture life at the lower forging temperatures.

The response of rupture life to DA processing was rather unexpected. Rupture life increased significantly over SA levels with increasing forge temperature except for a notch failure which occurred at 1093°C. Further testing, including other temperatures and stresses, should be done to see if these trends hold and if the mechanism can be determined.

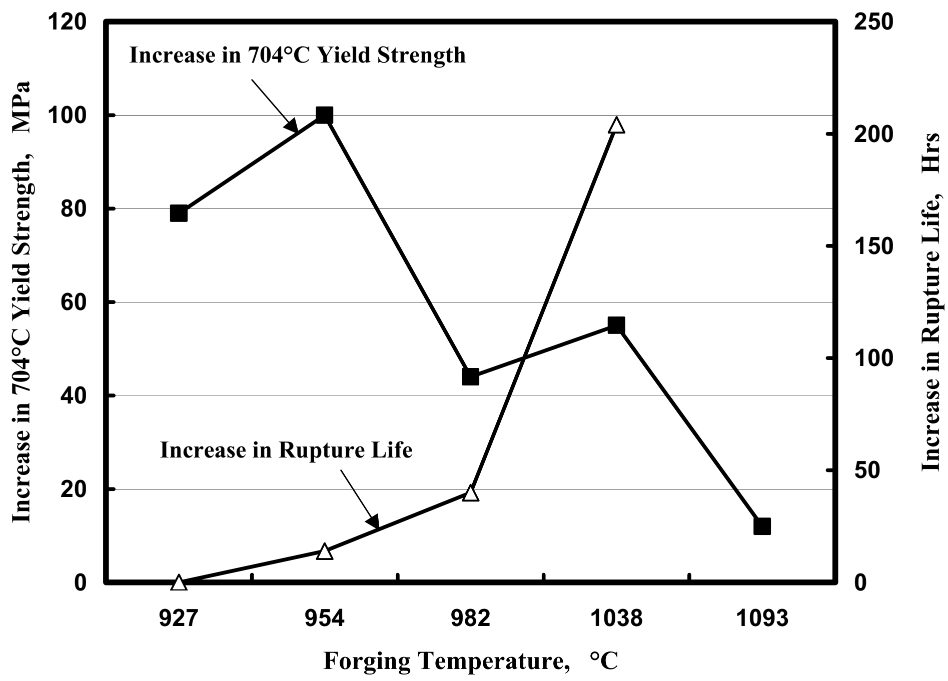


Figure 2. Difference in SA and DA Properties of Alloy 718Plus™ as a Function of Forge Temperature.

Figure 3 plots DA response to forging temperatures as relative (percentage) improvement in properties. The exact same trends are observed. These results suggest it may be possible to tailor a DA forge practice for alloy 718Plus to optimize a particular set of properties, depending on the specific final part requirements. Forging in the range of 982°C to 1038°C for example gave DA tensile strengths slightly better than SA but much improved rupture lives. Forging from 954°C or below, including additional room temperature cold work, greatly increased tensile strength but there was little or no increase in rupture life.

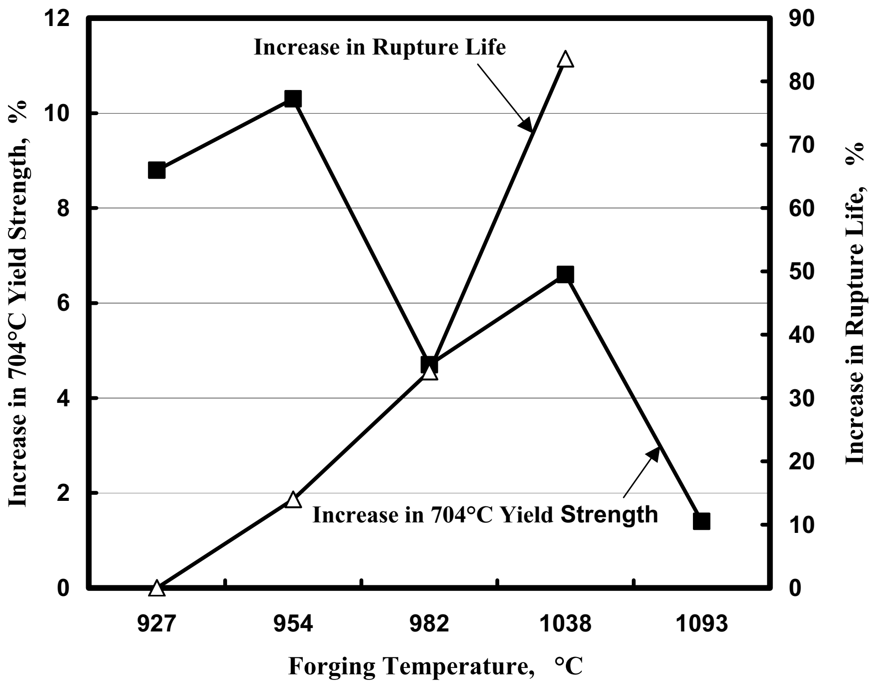
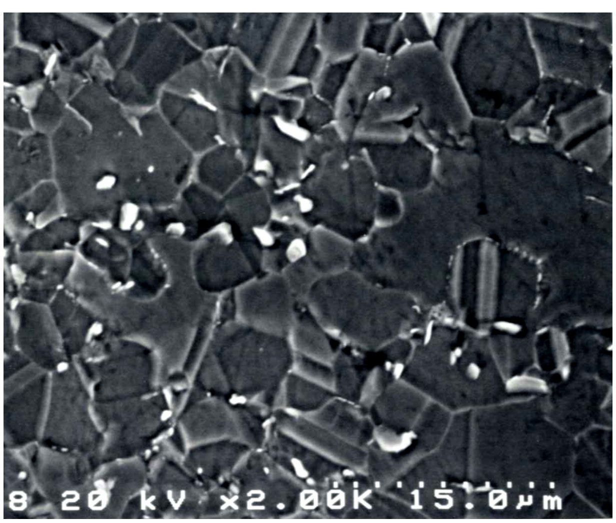
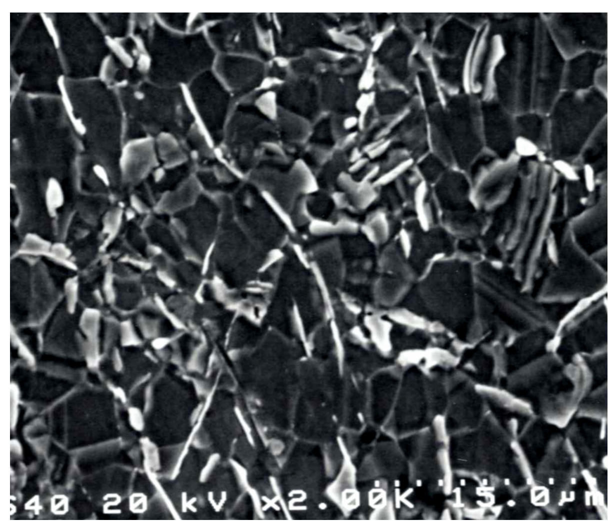


Figure 3. Percentage Change in SA and DA Properties of Alloy 781Plus™ as a Function of Forge Temperature.

This study also demonstrated that forging heating time can influence the effectiveness of direct aging in this alloy. Long heating time at the lower forge temperatures (954°C and lower) is detrimental due to extensive δ phase precipitation, as shown in Figure 4. Heavy δ phase formation significantly reduces the content of available hardening elements, reducing mechanical properties after direct age treatment.



(a)



(b)

Figure 4. Effect of Heating Time on δ Phase Precipitation in Alloy 718Plus™ Forged at 954°C: (a) 30 minutes (b) 3 hours.

Results of the post-forging cooling rate testing showed little effect, suggesting cooling rate should not be a major barrier for applying direct aging in production of this alloy. The slowest post-forging cool rate used in this study is estimated to be roughly equivalent to the cooling rate at the center of a 250 mm thick section during water or oil quenching. However, further study is needed to define the effect of post-forging cooling at even lower rates. The degree of work in the last forging operation should also not be a major issue in producing DA forgings of alloy 718Plus. Upset reductions of only 12% to 20% resulted in the best properties.

According to previous studies, many factors contribute to the beneficial effect of direct aging. In addition to fine grain size, a refined substructure and high dislocation density and increased nucleation rate and refinement of precipitates may also play important roles. TEM work conducted in this study showed the expected dislocation network. An increase in the number of precipitates, but little change in their size, may indicate that the strengthening effect due to direct aging might partially come from the increase in the volume fraction of hardening phases.

Conclusions

1. Direct aging can be effectively applied to alloy 718Plus to improve its mechanical properties, including strength and stress rupture life.
2. Forging temperature is the most significant process variable. The optimum forging temperature was found to be from 927°C to 1038°C. Lower working temperatures of 954°C and below led to significant improvement in strength. A large and somewhat unexpected increase in rupture life resulted from DA heat treatment of forgings made at 982°C to 1038°C.
3. Other forging variables studied, including heating time, upset reduction and post forging cooling rate need to be considered in making forgings, but had a much lesser effect on properties.
4. These results suggest that alloy 718Plus may be a suitable material for production of fine grain, very high strength DA forgings.
5. Another interesting process variant for alloy 718Plus might involve forging to produce an intermediate grain size (ASTM 6 to 8) followed by direct aging to achieve improved stress rupture life.
6. Additional work should be done to confirm the potential for improved rupture life, to explore the effects of test temperature and to measure creep rates and fatigue crack growth rates.

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