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High Temperature Fatigue Crack Growth Behavior of Alloy 10

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INTRODUCTION

Gas turbine engines for future subsonic aircraft will probably have higher pressure ratios which require nickel-base superalloy disks with 1300 to 1400°F temperature capability. Several advanced disk alloys are being developed to fill this need. Under NASA's AST Program, manufacturing technologies for two advanced disk alloys were studied by a team representing four engine companies, GEAE, PWA, Honeywell (Allied Signal), and Allison. GEAE and PWA focused their attention on an advanced disk alloy suitable for large engine applications developed under NASA's HSR Program, while Honeywell and Allison opted to focus their attention on Alloy 10, a high strength nickel-base disk alloy, which was developed by Honeywell for application in smaller gas turbine engines. The initial evaluation, i.e. tensile and creep properties, of Alloy 10 were run under the AST Disk Program (Reference 1). However, due to funding limitations, fatigue and crack growth evaluation were moved to NASA's Ultrasafe and UEET Programs.

This paper describes Alloy 10 crack growth studies conducted under Ultrasafe and UEET. The crack growth program was divided into two parts. The first part of this study was designed to evaluate the effects of solution temperature, cooling rate, and stabilization on crack growth. The second part of this study was designed to evaluate the effects of niobium and tantalum on crack growth. Previous work under NASA's HSR Program has shown that heat treatment and alloying additions can have dramatic effects on crack growth rates of nickel-base superalloys at elevated temperatures.

MATERIAL AND PROCEDURES

Alloy 10 is a high strength nickel-base superalloy, with a gamma prime content of about 55%. Evaluation of heat treat parameters on crack growth rates were run using existing forgings from the AST Program, while alloying effects were studied using small extrusions to stay within overall budget constraints. The compositions of baseline Alloy 10 and the Alloy 10 mods are presented in Table I.

The forgings were produced from argon atomized powder which was HIPed and extruded to 6" diameter billet. Mults were cut from the billet and isothermally forged into "pancake" shapes about 14" in diameter and 2" thick. Six forgings were given different heat treatments, defined in Table II. As previously stated, these heat treat options were designed to study the effect of solution temperature, cooling rate, and stabilization. Three solution temperatures were employed, 2125, 2160, and 2190°F. These solution temperatures were intended to produce target grain sizes of ASTM 11, 8, and 6 respectively. As cooling rate from the solution temperature can impact mechanical properties it was varied as follows. Fan cooling, which gives moderately fast cooling rates, was applied at all three solution temperatures. A faster cooling rate, produced by oil quenching, was also tried at 2125°F. The effect of a stabilization treatment, 1550°F for 4 hours, was studied for oil quenched forgings with the 2125°F solution treatment and fan cooled forgings with the 2190°F solution treatment. Stabilization treatments are used to minimize residual stresses, but are also known to impact mechanical properties by coarsening gamma prime precipitates and promoting the formation of $Cr_{23}C_6$ carbides. A final age, 1400°F for 16 hours, was also applied as the last step in all heat treatments.

The Alloy 10 modifications listed in Table I were designed to study the effects of changes in the niobium and tantalum content on crack growth, especially dwell crack growth. Compared to the baseline chemistry, tantalum levels were increased while niobium levels were decreased. The rationale for these choices were tied to the opinion that niobium accelerates crack growth while tantalum retards crack growth. As previously stated, material for this part of the study was obtained from small extrusions, produced from argon atomized powder which was compacted and extruded to 3" diameter billet. EDM was used to prepare heat treat blanks, 0.5"diameter by 3" long. These blanks were then solutioned at 2100F to obtain a fine grain, subsolvus microstructure or 2190F to obtain a coarse grain, supersolvus microstructure. The small blanks were air cooled and subsequently aged at 1400F for 16 hours.

Crack growth rates were determined using a surface-notched specimen shown in Figure 1. The details of the test procedure are described in Reference 2. However, in brief, testing consisted of precracking the specimen at room temperature followed by elevated temperature crack growth measurement using a potential drop system for accurate determination of crack growth rates. As high temperature dwell crack growth rates of nickel-base superalloys often limit disk life, comparison of heat treat and composition effects on crack growth were made at 1300F with a 90 second dwell at peak load employing an R-ratio of 0.1. For the heat treat study the crack growth specimens were machined from the outer rim of the forgings such that the length of the test bar was parallel to the hoop direction. For the composition study, the crack growth specimens were machined such that the length of the test bar was parallel to the extrusion direction.

RESULTS AND DISCUSSION

Heat Treat Study. As heat treat also affects tensile properties, a short discussion of this topic is warranted. The 1300F tensile data are summarized in Table III. One can see increasing solution temperature (coarser grain size) results in less strength, while higher cooling rates increase strength. Both of these trends are expected, however, stabilization has little effect on strength, unlike other nickel-base disk alloys where stabilization often causes a pronounced drop in tensile strength (Reference 3).

Before comparing the effect of heat treatment on crack growth, an examination of the relation between temperature, dwell time, and crack growth rates for Alloy 10 will be made for the subsolvus, fine grain microstructure. Figure 2 shows that going from bore-like temperatures, 750F, to rim-like temperatures, 1300F, produce about a ten fold increase in cyclic crack growth rates. The addition of a 90 second dwell at 1300F produces a fifteen fold increase in cyclic crack growth rates. Further, the temperature dependency of the dwell cycle is quite dramatic, as shown in Figure 3, decreasing the temperature from 1300F to 1200F decreases dwell crack growth rate about ten fold. The high temperature dwell cycle simulates conditions encountered at the rim of a turbine disk during takeoff and landing of commercial jets. Therefore improving high temperature dwell crack growth resistance can enhance disk life.

The effect of heat treatment on 1300F dwell crack growth for Alloy 10 is presented in Figure 4. Several trends are immediately obvious. First, higher solution temperature (coarser grain size) produces a tremendous improvement. Second, stabilization produces a significant improvement for the supersolvus, coarse grain microstucture, and a modest improvement for the subsolvus, fine grain microstructure. Finally, increasing cooling rate (fan versus oil) for the subsolvus material is seen to have a somewhat detrimental effect on dwell crack growth rates. It appears that a supersolvus heat treatment with a stabilization cycle would be the preferred heat treatment for Alloy 10 from a crack growth standpoint. Further, adopting this philosophy does not appear to have a negative impact on crack growth rates at bore-like temperatures, as seen in Figure 5. However, coarse grain sizes decrease tensile strength, while stabilization is known to reduce creep properties of Alloy 10 (Reference 1). With these observations in mind, the use of advanced processing technologies, which can produce a coarse grain rim and a fine grain bore, would be the preferred option for Alloy 10 to obtain the optimal balance between tensile, creep, and crack growth requirements for turbine disks.

Composition Study. While heat treat offers options for improving crack growth resistance of Alloy 10, changes in composition may also provide improved crack growth resistance. With this in mind, niobium and tantalum effects were studied. As seen in Figure 6, significant changes in the alloy's niobium:tantalum ratio had minimal impact on subsolvus dwell crack growth resistance, although decreasing the ratio does appear to produce a small benefit. For the supersolvus, coarse grain microstructure the effect is more pronounced, although the maximum benefit is only about a two fold decrease in dwell crack growth rate on decreasing the niobium:tantalum ratio. It is interesting to note, that stripping all niobium from the alloy had very little effect, suggesting that increasing tantalum content was probably more important with respect to improving dwell crack growth resistance. Further, as shown in Table IV, removing all niobium from the alloy produces a significant drop in tensile strength.

SUMMARY AND CONCLUSIONS

Methods to improve the high temperature, dwell crack growth resistance of Alloy 10, a high strength, nickel-base disk alloy, were studied. Two approaches, heat treat variations and composition modifications, were investigated. Under the heat treat approach, solution temperature, cooling rates, and stabilization, were studied. It was found that higher solution temperatures, which promote coarser grain sizes, coupled with a 1550F stabilization treatment were found to significantly reduce dwell crack growth rates at 1300F. Changes in the niobium and tantalum content were found to have a much smaller impact on crack growth behavior. Lowering the niobium:tantalum ratio did improve crack growth resistance and this effect was most pronounced for coarse grain microstructures.

Based on these findings, a coarse grain microstructure for Alloy 10 appears to be the best option for improving dwell crack growth resistance, especially in the rim of a disk where temperatures can reach or exceed 1300F. Further, the use of advanced processing technologies, which can produce a coarse grain rim and fine grain bore, would be the preferred option for Alloy 10 to obtain the optimal balance between tensile, creep, and crack growth requirements for small gas turbine engines.

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1. S. K. Jain, "High OPR Core Material (AoI 4.2.4), Regional Engine Disk Development", Final Report, NAS3-27720, November 1999.
2. R. H. Vanstone and T. L. Richardson, Potential-Drop Monitoring of Cracks in Surface Flawed Specimens, ASTM STP 877, 1985, pp. 148-166.
3. J. C. Chesnutt, R. G. Tolbert, and D. P. Mourer, "High OPR Core Materials (AoI 4.2.5), Forging Process Definition – Alloy 2", Final Report, NAS3-27720, November 1999.

TABLE I. COMPOSITION OF ALLOY 10 AND MODS.												
	Co	Cr	Al	Ti	Mo	W	Nb	Ta	C	B	Zr	Ni
MOD 1	15.0	11.0	3.8	3.8	2.5	5.7	0.9	0.9	0.04	0.03	0.10	56.23
MOD 2	15.0	11.0	3.8	3.8	2.5	5.7	0.9	1.8	0.04	0.03	0.10	55.33
MOD 3	15.0	11.0	3.8	3.8	2.5	5.7	0.0	1.8	0.04	0.03	0.10	56.23
ALLOY 10	15.0	11.0	3.8	3.8	2.5	5.7	1.8	0.9	0.04	0.03	0.10	55.33

TABLE II. HEAT TREAT MATRIX FOR ALLOY 10 FORGINGS.				
ID	SOLUTION	STABILIZE	AGE	GRAIN SIZE
SUB/FAN	2125F/2.5HR/FAN	NONE	1400F/16HR/AC	ASTM 11.3
SUB/OIL	2125F/2.5HR/OIL	NONE	1400F/16HR/AC	ASTM 11.5
SUB/OIL/STAB	2125F/2.5HR/OIL	1550F/4HR/AC	1400F/16HR/AC	ASTM 11.5
NEAR/FAN	2160F/2.5HR/FAN	NONE	1400F/16HR/AC	ASTM 7.9
SUP/FAN	2075F/1HR+2190F/2.5HR/FAN	NONE	1400F/16HR/AC	ASTM 6.1
SUP/FAN/STAB	2075F/1HR+2190F/2.5HR/FAN	1550F/4HR/AC	1400F/16HR/AC	ASTM 6.4

TABLE III. 1300F TENSILE DATA FOR ALLOY 10 FORGINGS.				
ID	0.2% YIELD(KSI)	UTS (KSI)	ELONG(%)	GRAIN SIZE
SUB/FAN	163	193	9	ASTM 11.3
SUB/OIL	175	203	8	ASTM 11.5
SUB/OIL/STAB	174	202	8	ASTM 11.5
NEAR/FAN	159	197	16	ASTM 7.9
SUP/FAN	151	195	17	ASTM 6.1
SUP/FAN/STAB	152	195	19	ASTM 6.4

TABLE IV. 1300F TENSILE DATA FOR ALLOY 10 MODS.				
Nb:Ta RATIO	0.2% YIELD(KSI)	UTS (KSI)	ELONG(%)	GRAIN SIZE
1.7	172	203	9	ASTM 11.8
0.8	167	199	11	ASTM 11.4
0.4	169	201	10	ASTM 12.0
0.0	164	196	12	ASTM 11.6
1.7	167	212	16	ASTM 7.7
0.8	160	204	18	ASTM 7.6
0.4	162	207	17	ASTM 7.9
0.0	156	200	19	ASTM 8.1

FIGURE 1. DESIGN OF CRACK GROWTH SPECIMEN.

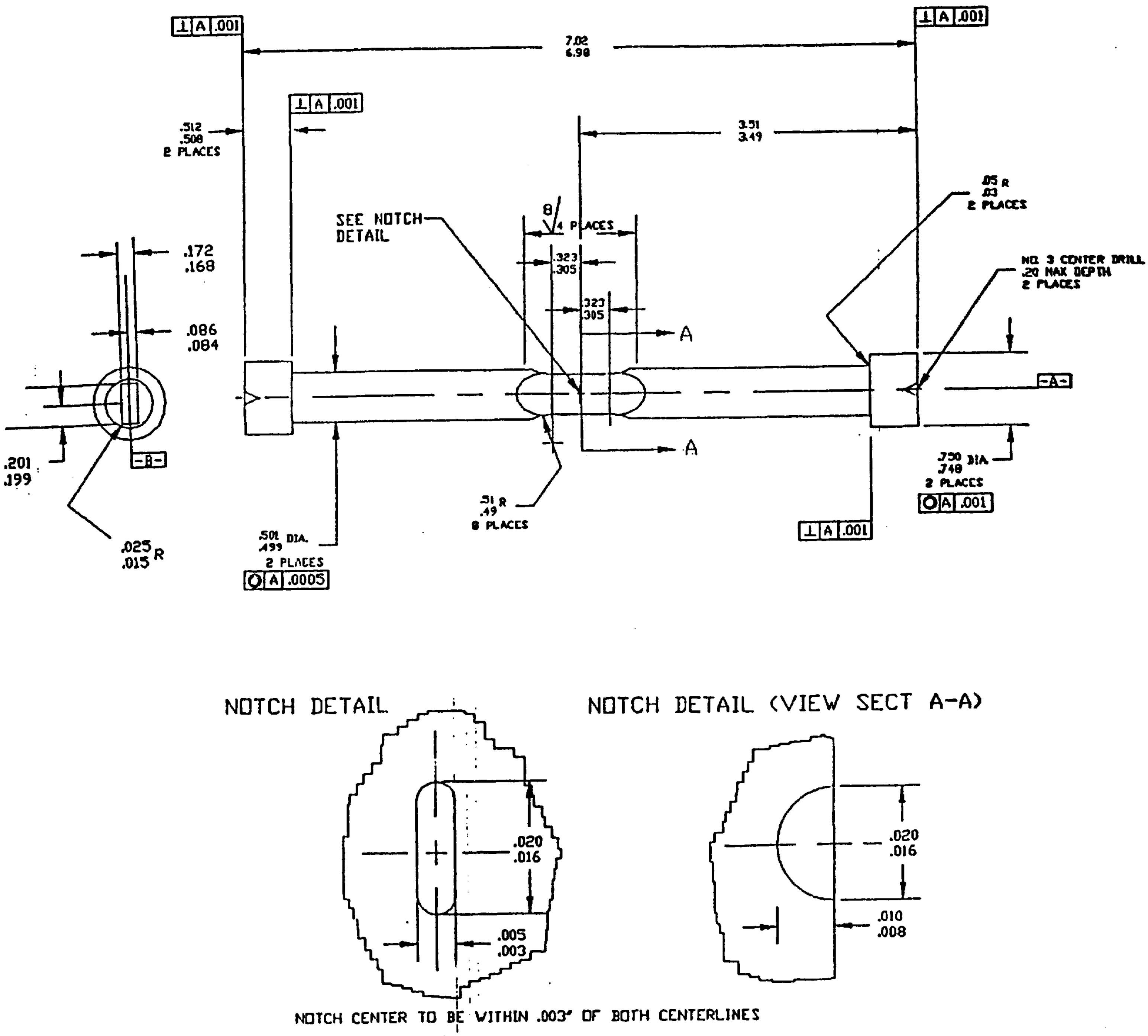


FIGURE 2. CYCLIC CRACK GROWTH DATA FOR SUBSOLVUS/FAN COOLED HEAT TREAT.

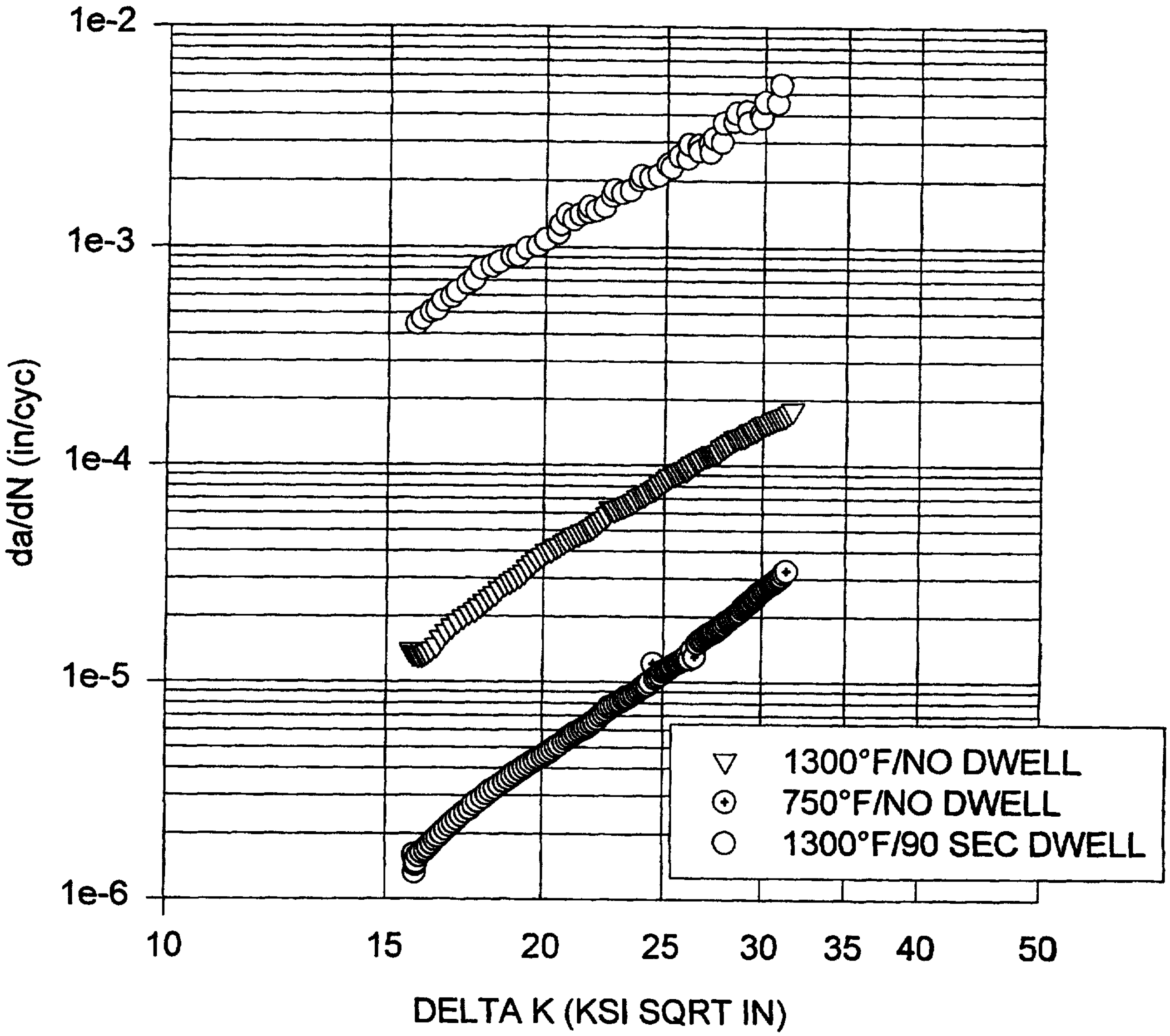


FIGURE 3. TEMPERATURE EFFECT ON DWELL CRACK GROWTH DATA FOR SUBSOLVUS MICROSTRUCTURE.

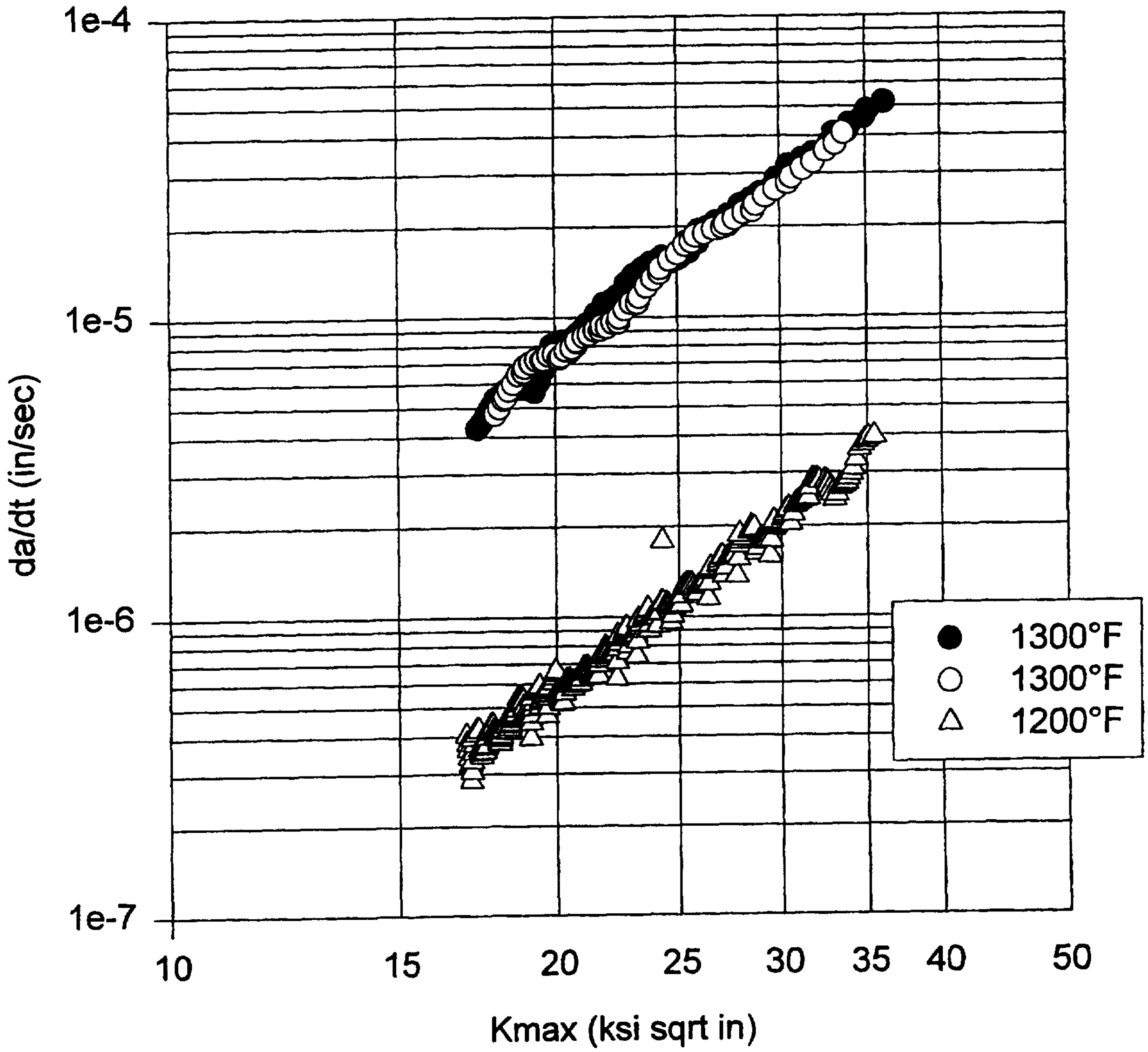


FIGURE 4. EFFECT OF HEAT TREATMENT ON DWELL CRACK GROWTH DATA FOR ALLOY 10.

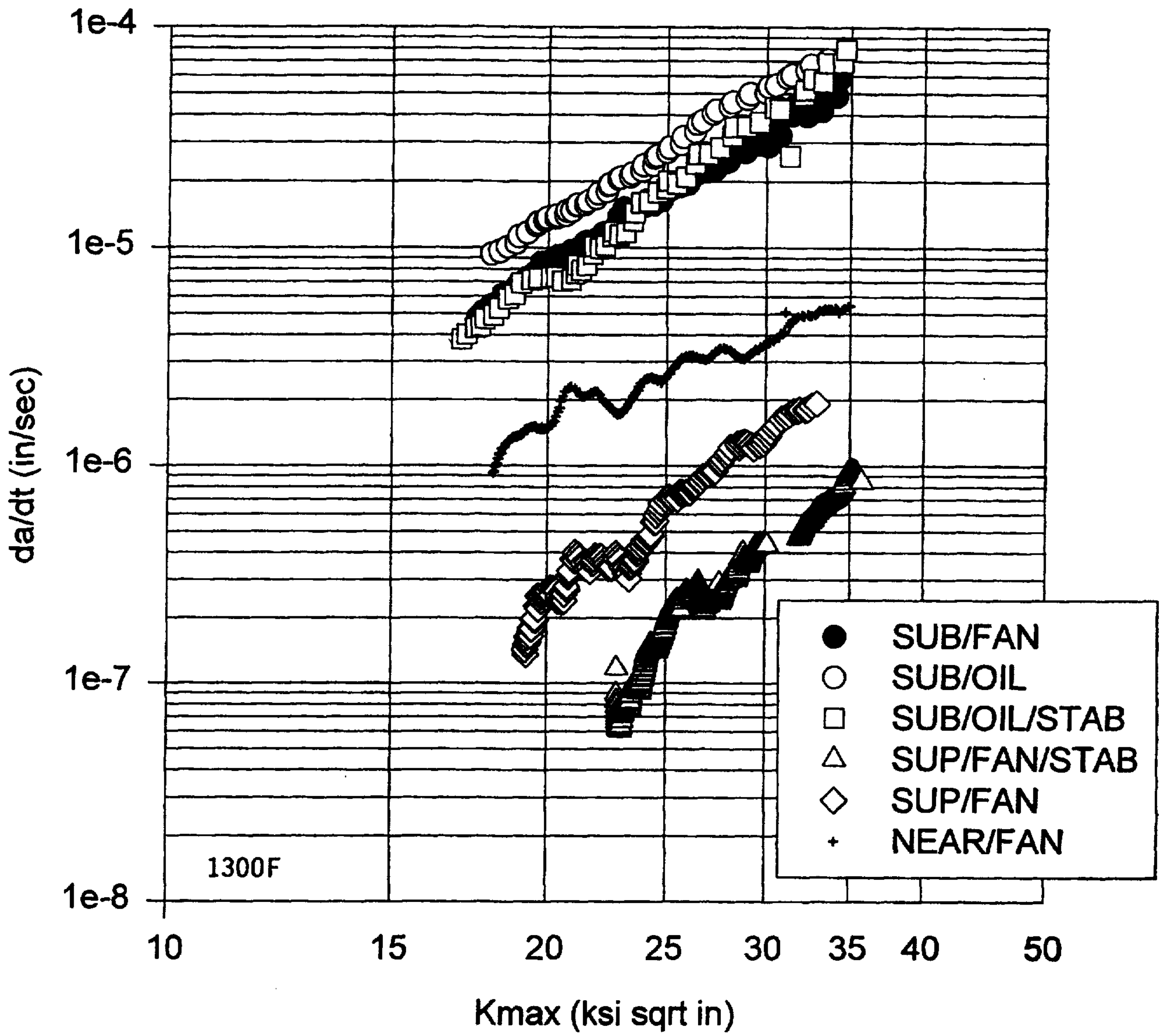


FIGURE 5. EFFECT OF HEAT TREATMENT ON CYCLIC CRACK GROWTH DATA FOR ALLOY 10.

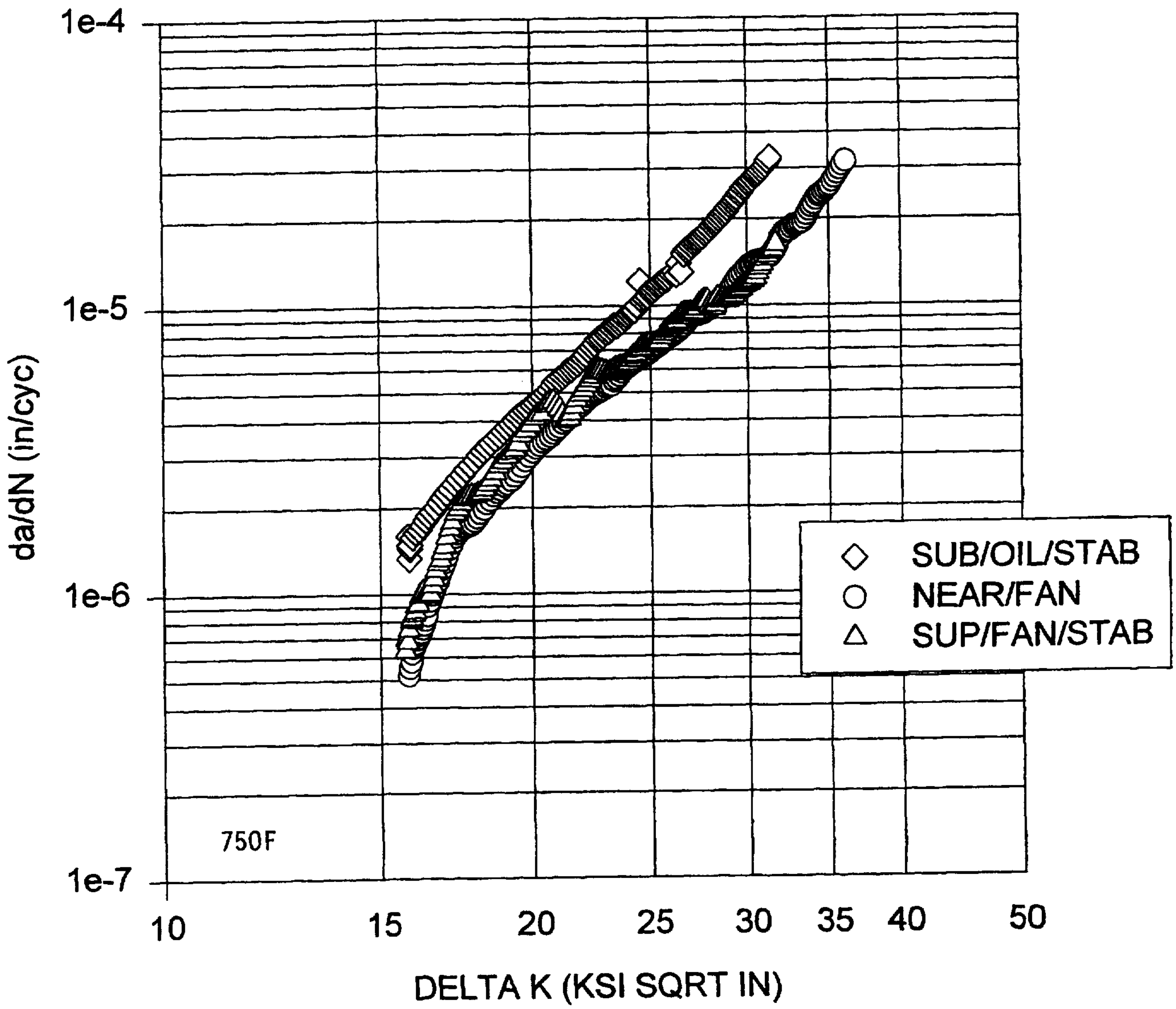
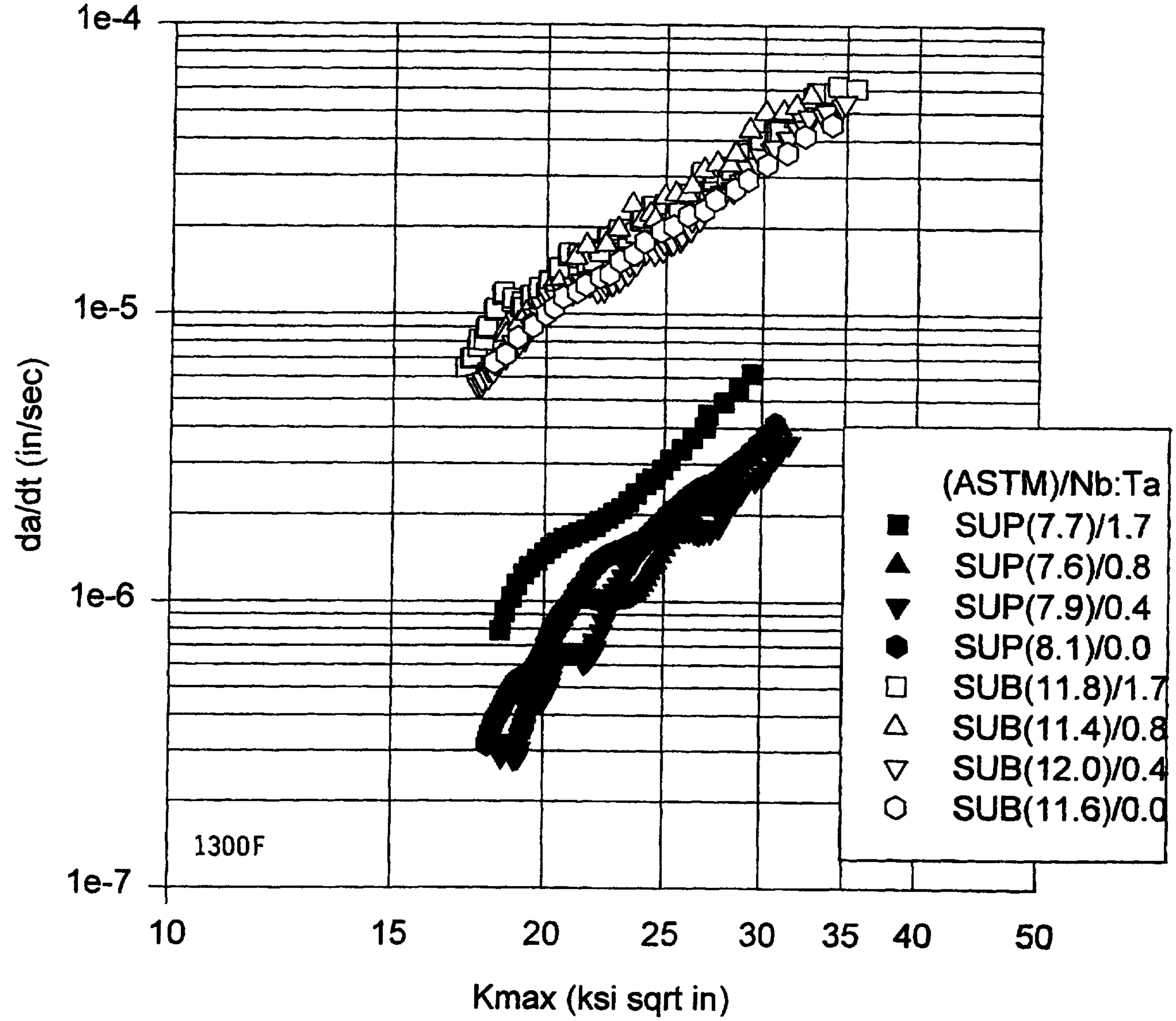


FIGURE 6. EFFECT OF NIOBIUM: TANTALUM RATIO ON DWELL CRACK GROWTH DATA.



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13. ABSTRACT ***(Maximum 200 words)***

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