"DEVELOPMENT OF FORGING AND HEAT TREATING PRACTICES FOR AMS 5737 FOR USE AT LIQUID HELIUM TEMPERATURES"

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Introduction:

To achieve a combination of high yield-strength (K_{1p}), plane-strain fracture-toughness (K_{Ic}) and resistance to galling when turned against austenitic stainless steels in highly-loaded threaded turnbuckles in the N.K.L. 4000 Barren Vactor Test Facility, 4K-5737 (AMS 5737) (Al-5.5%Ti-4%Zr) heat-treatable Fe-base superalloy that is slightly-ferromagnetic under high magnetic fields at 4K, was chosen for large (c. 340 kN) forged turnbuckles. This report describes the forging and heat-treatment optimization program that resulted in K_{Ic} and K_{1p} over the 1-300K range of service-temperatures and the verification tests run on a pre-production forging and actual production parts.

Procedure:

Because of a tendency towards notch-brittleness if incorrectly thermally-treated^{1,2,3,4}, a pre-production forged block was manufactured by a combination of double upsetting and cross drawing a piece of 4000 Barren Vactor billet conforming to AMS 5737 (Table 1) to a 76 mm (3 in.) x 4 mm (1/4 in.) piece that is representative of the rough-forged condition. The forging temperature was heated to 1294K to 1300K (1020°C to 1030°C) and forged temperature was maintained for 10 minutes. The block was solution treated to yield a fine grain size in the threaded portion, appropriate to good low temperature toughness. Since the rate of grain growth during solution-treatment is proportional to the grain diameter to a power of 2, it was necessary to determine the minimum time at 1173K to ensure complete solutioning of alloy additions. This was accomplished by cutting an 89 mm thick transverse slice from the pre-production forging, quartering the slice, and heat-treating the quartered pieces for 1, 2, 4, and 24 hours at 1173K, followed by oil-quenching. Standard round smooth and notched ($K_t=3$) tensile specimens and metallographic specimens were machined from the first 3 slices, and a metallographic specimen was machined from the fourth slice to check for eta phase formation⁴. A K_t of 3 was chosen to match that anticipated to be created in the threaded portion of the turnbuckle under load.

After optimization of the post-forging solution-treatment time, smooth and notched ($K_t=2$) tensile specimens and elastic-plastic fracture toughness specimens were removed from the remainder of the pre-production forging. Tensile specimens were removed from near the surface of the forging, oriented in both the longitudinal and tangential directions.

Fracture-toughness specimens were oriented so that the crack grew in the longitudinal direction in a radial plane (F-L designation per ⁶). Tensile specimens, both smooth and notched ($K_t=3$) oriented in both the longitudinal and tangential directions, were also removed from prolongations on selected production-forgings. All specimens were given a standard acid treatment of 7188 (16 hrs.) air cool.

Room temperature tensile testing was done in a 40-k ton electro-hydraulic tensile testing machine per ⁷. Tensile testing at 4K was done in a "Super" split-hearth (4.15 ton per ⁸). Single specimen Charpy-plasticity-toughness tests at 200K and 4K were done in a 10-ft facility per ⁹. Metallographic specimens were prepared by standard methods and examined as described in ⁶.

Results

Chemical analyses of 3 heats of AMS 6224 used in manufacture of the one pre-production and 14 production forgings are given in Table 1. The requirements of AMS 6224 were met. Table 2 summarizes tensile and fracture toughness test results, the latter quantity being reported as K_{IC} converted by the method discussed in ¹⁰.

Table 3 summarizes the results of the study to optimize solution-treatment time at 1174K, presented in Table 1 and Fig. 1. A time of 7 hours at 1174K was an excellent compromise between maximizing strength and elongation (shorter times) and maximizing ductility (longer times). A metallographic specimen exposed for 24 hours at 1174K (not shown) contained excessive eta precipitates ¹¹, indicative of poor wetting-temperatures.

Table 4 reports the 4K and 200K results on the pre-production forging given the new 7-hour 1174K solution-treatment; several points are apparent:

1. Tensile properties at 200K exceed the requirements of AMS 6224;
2. Tensile properties at 4K show higher ultimate tensile strength (σ_u , 121KSI vs 114KSI), elongation to fracture ϵ_f (48%) and lower reductions in area (RA) (48%) and lower tensile-strengths ratio (NTR) (4%), based upon longitudinal properties, relative to the results obtained from the solution-treatment optimization-study;
3. 4K K_{IC} (avg.) of $132.7 \text{ MPa}\sqrt{\text{m}}$ is excellent, and is based on the average of two specimens one with a K_{IC} of $108.6 \text{ MPa}\sqrt{\text{m}}$, the other with a K_{IC} of $156.9 \text{ MPa}\sqrt{\text{m}}$. K_{IC} at 300K is $126.3 \text{ MPa}\sqrt{\text{m}}$.
4. Tangential tensile properties at 4K exhibit higher σ_u and ϵ_f and decreased ϵ_f , RA, and NTR values, relative to 4K longitudinal properties.

Regarding last the 300E tensile properties of longitudinal and tangential specimens removed from production-forgings, the requirements of AMS 5737H on σ_u , σ_y , and ϵ_f were surpassed. Both these properties and the RA and NTF values were comparable to results obtained from the tests on the pre-production forging.

Discussion:

Examination of microstructures taken from *41* removed tensile specimens oriented in the longitudinal (Fig. 3A, 3A') and tangential (Figs. 3B, 3B') directions indicates that while both specimens have the same matrix grain-structure, the former specimen shows no preferential pining of second-phases such as Pb_3Ni , etc. (see "a" plate), while the latter specimen shows extensive banding occurring at an angle of about 45° to the tensile axis (preferential in photomicrographs), compare Fig. 2A and 2A'. At higher magnification (Fig. 2B), the banded nature of second-phases is more clearly visible, with the greatest banding, and the increase in tie between the longitudinal (NIST, 21) and tangential (NIST, 22) orientations of *41* is explainable on the basis of preferential fracture through bands of less-toughness second-phases.

A similar explanation is proposed as the reason for increases in ϵ_f and σ_y values from smooth longitudinal tensile specimens tested to optimize solution-treatment time to smooth longitudinal specimens to smooth tangential specimens tested after removal from the pre-production-forging, as shown below:

Treatment	Orientation	MPa		%	
		σ_u	σ_y	ϵ_f	RA
Pre-production forging					
Longitudinal					
Tangential					
Solution-treated					
Longitudinal					
Tangential					
Pre-production forging					
Longitudinal					
Tangential					

The increase in σ_u and σ_y is explainable in terms of an increased grain-size between the first versus the second and third sets of test results, while the decrease in ϵ_f and RA is explainable by the preferential fracture through bands of second-phase particles (Fig. 3B).

The large difference in δE_{KIP} between the two specimens tested is explained on the basis of occurrence of increasing amounts of quasi-cleavage in the less-tough specimen. Compare Figs. 4 and 5. The fracture-surface of the tougher specimen, with a K_{IC} of 156.3 MPa $\sqrt{m}$ (Fig. 4) consists of elongated dimples (Fig. 4A) with one isolated area of

quasi-cleavage (Fig. 4B). The fracture-surface of the less-tough specimen, with a K_{IC} of $108.6 \text{ MPa}\sqrt{\text{M}}$, consists of mixed areas of elongated dimples and quasi-cleavage (Fig. 5A, B), with an occasional grain-boundary separation (Fig. 5A).

Conclusion:

A double upset and cross draw forging sequence, with finish-forging in the 1172-1200K range, followed by a heat treatment of 1172K (2 hrs.) oil-quench, 718K (16 hrs.) air cool, produced useful combinations of smooth and notched ($k_t=3$) tensile and K_{IC} performance in large AMS 5737 forgings over the range 4-300K. Differences in mechanical properties were explained on the basis of microstructure differences arising from the forging-practice.

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Table One
CHEMICAL COMPOSITION OF AMS 5737

Heat no.	Forging temp., °F.	C	Mn	P	S	Si	Composition, weight percent						V	Ti	B
							Fe	Al	Mo	Ni	Cu	Co			
9 6673	17,412	0.05	0.14	0.01	0.002	0.52	100	1.49	0.26	0.32	26.8	14.2	0.23	2.22	0.007
9 7261	16,17	0.04	0.14	0.011	0.004	0.40	100	1.29	0.20	0.21	24.6	14.8	0.24	2.28	0.008
9 7086	15	0.04	0.14	0.013	0.003	0.50	100	1.32	0.16	0.28	24.9	14.2	0.25	2.29	0.006
AMS5737H	2000	0.04	0.14	0.025	0.025	1.00	100	1.50	0.35	0.27	27.00	15.00	0.50	2.35	0.01
							100				24.00	13.50	0.10	1.90	0.003

† Not reported or specified.
* Maximum unless a range is quoted.

Table Two

MECHANICAL PROPERTIES OF AMS 5737 FORGINGS

Orient.	Time at 1172K* (hours)	Test temperature (K)	Optimization time at 1172K			Reduction area (%)	Notch UTS*** Smooth UTS	Plane strain true stress
			Y. strength (MPa)	0.2% proof strength (MPa)	Elongation 25.4 mm (%)			
Longitudinal**	1	4	1199	971	22.0	18.6	1.40	***
	2		1212	790	23.5	33.7	1.36	
	4		1233	806	29.0	36.9	1.31	
Properties of parts cut from forgings								
Longitudinal*	2	4	1506	1047	25.5	22.7	1.31	132.7 MPa _{√m}
Tangential**	2		1551	1128	19.0	17.4	1.18	
Longitudinal*	2	300	1098	823	21.5	30.7	1.40	136.3
Tangential**	2		1093	801	20.0	25.3	1.38	
Properties of specimens cut from production forgings								
Longitudinal*	2	300	1044-1063 1053	807-809 808	20.6-21.0 20.8	26.7-52.5 29.6	1.38-1.44 1.41	
Tangential**	2		992-1099 1038	766-821 792	19.0-21.0 20.4	27.7-30.8 30.0	1.34-1.44 1.39	
AMS 5737H (min values)			965	631	12.0	15.0		

Notes

* 1172K (2 hrs), oil quench; 718K (16 hrs), air cool

** Single specimen

*** K_{IC} = 3.0

* Average of 2 specimens

** Average of 5 specimens

*** Converted from J integral test results

MAG: X250

MAG: X1050

FIGURE 1: TRANSVERSE SECTION THROUGH SAMPLE 2N, AFTER A POST-FORGING HEAT-TREATMENT OF 1172K (2 HRS.) OIL-QUENCH, PLUS 718K (16 HRS.), AIR-COOL, AND TENSILE-TESTING AT 4K.

NOTE MC-TYPE CARBONITRIDES (1), WIDMAN STATION-TYPE OF PHASE (2), A GRAIN-BOUNDARY PHASE (3), POSSIBLY "G" PHASE, AND AN UNIDENTIFIED INTRA-GRANULAR PRECIPITATE (4).

FIGURE 2: MICROSTRUCTURE OF NOTCHED TENSILE SPECIMENS TESTED AT 4K. NOTE HEAVY BANDING OF SECOND PHASES AND FINE GRAINED REGIONS (ARROWS) IN TANGENTIAL SPECIMEN, AND ABSENCE OF SAME IN LONGITUDINAL SPECIMEN.

-B-

-A-

FIGURE 3: MICROSTRUCTURE OF FRACTURES IN NOTCHED TENSILE SPECIMENS TESTED AT 4K. NOTE SECONDARY-CRACKING ASSOCIATED WITH MC TYPE CARBONITRIDES (A), HEAVY BANDING OF SECOND PHASES AND FINE GRAINED REGIONS (B) IN TANGENTIAL SPECIMEN, AND ASSOCIATION OF PRIMARY FRACTURE (C) WITH (B).

X1500

X2000

FIGURE 4: FRACTURE SURFACE OF 4K K_{IC} SPECIMEN 381,
SHOWING ELONGATED DIMPLES, QUASI-CLEAVAGE,
AND A GRAIN-BOUNDARY FILM (A).

A

X999

B

X1007

FIGURE 5: FRACTURE-SURFACE OF $4K K_{IC}$ SPECIMEN 3C1, SHOWING QUASI-CLEAVAGE, A GRAIN-BOUNDARY CRACK (A), AND ELONGATED DIMPLES.