OPTIMIZATION OF THE FATIGUE PROPERTIES

OF INCONEL ALLOY 625

Gaylord D. Smith and Daniel H. Yates

Inco Alloys International, Inc.
P. O. Box 1958
Huntington, West Virginia 25720

Abstract

Melt practice, rigorous control of certain alloying elements and annealing practice can directly influence key characteristics which aid in optimizing LCF properties of INCONEL® alloy 625. These procedures can favorably influence grain size, inclusion types and count and mechanical properties. It is shown how an optimum combination of these procedures can greatly improve LCF properties of alloy 625.

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Introduction

Conventionally used sheet and strip alloys in aerospace applications are often low cycle fatigue (LCF) and/or thermal fatigue (TF) limited in service. Combustors, transition ducts, exhaust systems, thrust reverser assemblies and afterburners are examples of gas turbine components which experience these modes of failure. An alloy, such as INCONEL alloy 625, is typically used for these engine components. Manufacturers of these products have a degree of latitude within established specifications to influence this type of alloy's performance within certain limits. A number of manufacturers' processing steps can directly influence key characteristics of their wrought alloys which, in turn, aid in optimizing LCF and TF properties. Paramount among these processing steps are melt practice, rigorous control of certain alloying elements and, finally, annealing practices. These procedures can act additively and even synergistically to favorably influence grain size, inclusion types and count and importantly, mechanical properties. An optimum combination of these characteristics can greatly improve LCF and TF properties of conventional wrought high nickel alloys. This paper describes for INCONEL alloy 625 a systematic evaluation of the effects of several key manufacturing options on mechanical properties, inclusion types and counts and grain size. These, in turn, are related to LCF at 538°C and 593°C. Manufacturing variables are also correlated with thermal fatigue life.

INCONEL alloy 625, UNS NO6625, (20–23% Cr, 8–10% Mo, 3.15–5.15% Nb + Ta, 1% max. Co, 5% max. Fe, 0.5% max. Si, 0.5% max. Mn, 0.4% max. Al, 0.4% max. Ti, 0.10% max. C, Bal. Ni) has proven to be valuable in numerous aerospace applications due to its high strength and toughness from cryogenic temperatures to 1095°C. The alloy is largely solid solution strengthened with molybdenum and niobium with some aging at 593°C and above due to Ni_3Nb. Its high temperature fatigue strength is useful and, if optimized, can be exceptional.

Procedure

Initially, a conventional heat of air melted, AOD processed and electroslag remelted (ESR) INCONEL alloy 625 was selected for characterization. The compositions of this study are presented in Table I. Strip from the AOD plus ESR heat was given a standard anneal in hydrogen at 1175°C/0.5 minute and evaluated for grain size, inclusions and tensile properties to 816°C. The LCF properties were measured under stress controlled tension–tension test conditions. On an additional heat, the annealing temperature was reduced to 1065°C/0.5 minute, thus reducing grain size and increasing the room temperature (RT) yield strength. Subsequently, the melt practice was changed to vacuum induction melting (VIM) plus ESR. Strip from this heat was given a 1065°/0.5 minute anneal and fully tested as above, including LCF characterization. Using a similar heat, total strain control LCF data were also determined. Finally, a VIM plus ESR melt practice heat was produced with restricted levels of silicon, carbon and nitrogen. The strip was again characterized after a 1065°C/0.5 minute anneal. The specimens from the AOD plus ESR melt practice heat using a 1175°C/0.5 minute anneal and the VIM plus ESR melt practice heat at 1065°C/0.5 minute were TF tested in a 890°C to 150°C thermal cycle (40 minutes in the hot zone and 10 minutes in the cold zone).

Table I - INCONEL alloy 625 Compositions of This Study (weight percent)

Heat	C	Si	Ni	Cr	Mo	Nb	Fe	Al	Ti	Mn	N
Strip Heats											
NX4235AG[1]	0.02	0.25	61.07	21.71	8.50	3.53	4.33	0.18	0.24	0.16	0.02
NX4267AG[1]	0.03	0.22	61.52	21.63	8.51	3.55	3.93	0.19	0.23	0.18	0.02
NX0078AK[2]	0.03	0.11	61.71	21.90	8.49	3.37	3.84	0.21	0.24	0.08	0.01
VX0836AK[2]	0.02	0.05	59.82	22.19	9.04	3.52	4.45	0.40	0.13	0.05	0.02
VX0057AK[2]	0.01	0.06	60.87	22.14	8.52	3.40	4.49	0.20	0.24	0.06	0.008
VX0764AK[2]	0.03	0.09	61.26	21.34	9.34	3.50	3.95	0.21	0.21	0.05	0.02
Bar Heat											
VX0343AK[2]	0.01	0.11	60.96	21.98	8.62	3.3	4.46	0.26	0.24	0.01	0.003

[1]AOD + ESR [2]VIM + ESR

The LCF tests were performed in air using both a stress controlled tension–tension–ratio axial mode (test frequency (f) = 59 Hz) and a fully reversed (strain ratio of R = -1) axial strain control mode, employing a symmetrical triangular strain wave cycle (f = 0.5 Hz). The fatigue testing apparatus was a Model 880 MTS closed loop servohydraulic system. Test temperature was achieved using an electrically heated furnace mounted on the test stand. Axial strain was measured and controlled by an axial gauge length extensometer mounted on the test specimen.

The fatigue specimens were taken transverse to the rolling direction of the sheet. Specimen blanks for the stress controlled fatigue testing were ground to 170 mm x 12.5 mm x gauge before a central gauge section of 12.5 mm x 7.6 mm x gauge was machined. The axial strain controlled LCF specimens were machined as shown in Figure 1. Grain size was established metallographically using a phosphoric etchant on speciments taken from the gauge length after LCF testing.

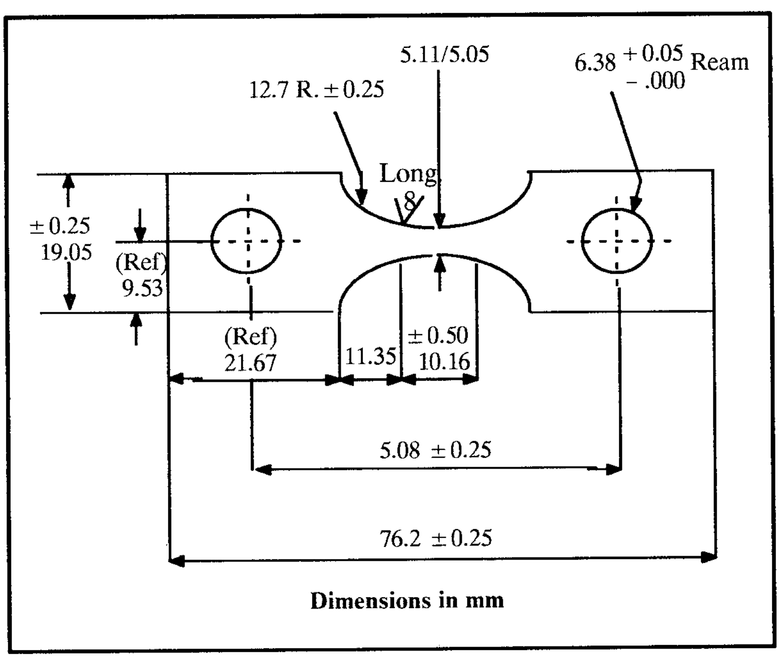

Figure 1. Schematic of the Axial Strain Controlled Sheet Specimen (maximum gauge thickness 2.5mm).

Results

The tensile properties to 816°C for four heats of the nominal INCONEL alloy 625 compositional range are presented in Figures 2 through 5 and their stress controlled tension-tension LCF properties are shown in Figure 6. These four heats were processed using differing melt practice and compositional limits on carbon, silicon and nitrogen as defined in the discussion section of this paper. The final anneal was also a variable for these heats. All four heats were rolled, using conventional practice, to 0.20 mm strip.

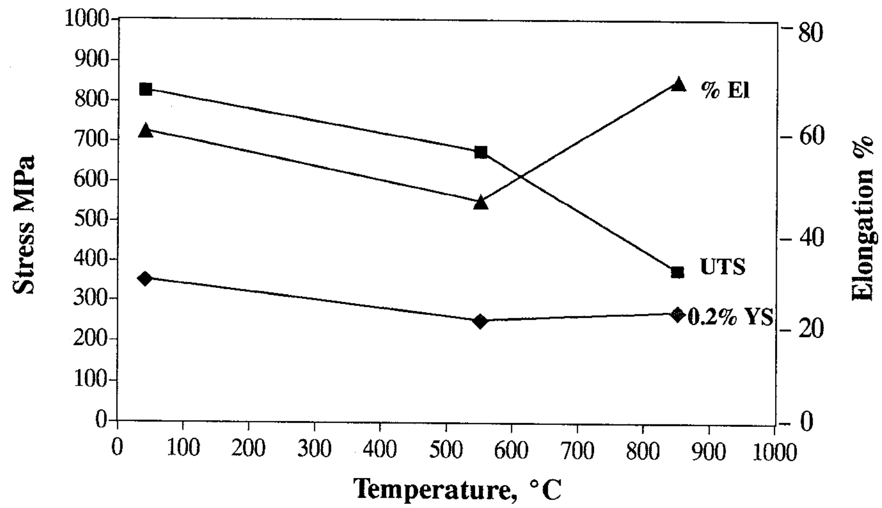

Figure 2. Tensile Properties to 816°C for AOD plus ESR Heat NX4235AG of alloy 625 Strip (0.20 mm gauge).

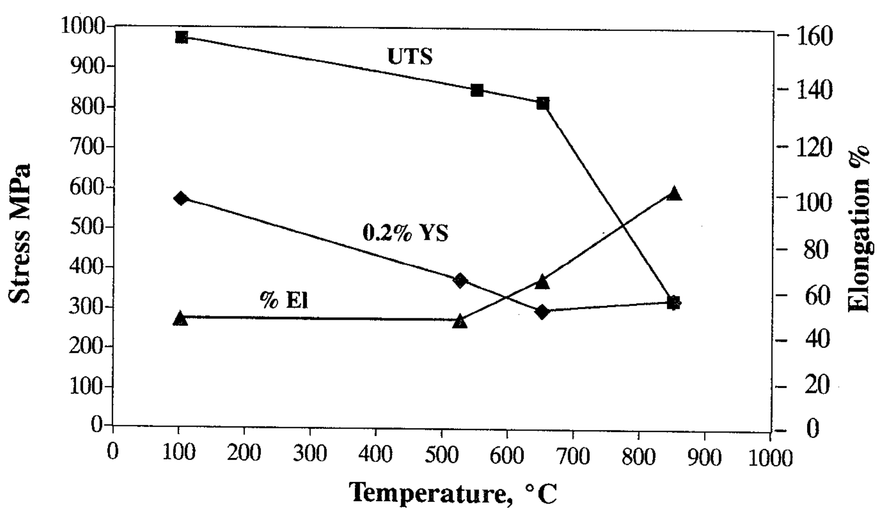

Figure 3. Tensile Properties to 816°C for AOD plus ESR Heat NX4267AG of alloy 625 Strip (0.20 mm gauge).

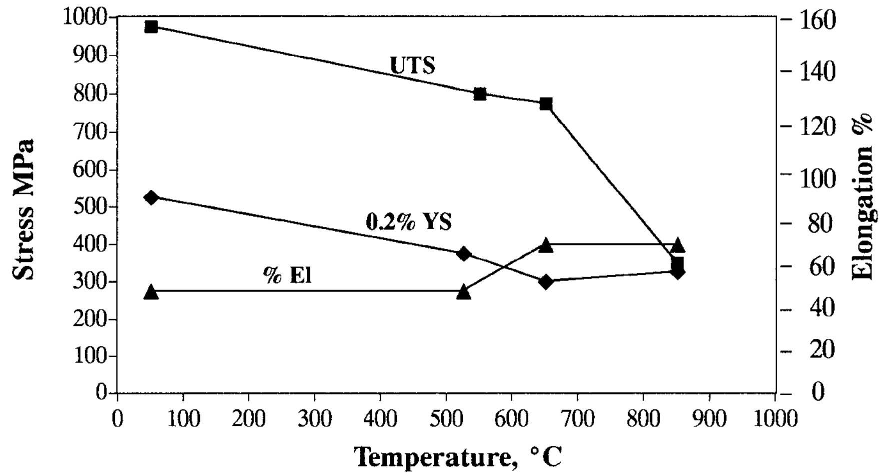

Figure 4. Tensile Properties to 816°C for AOD plus ESR Heat VX0078AK of alloy 625 Strip (0.20 mm gauge).

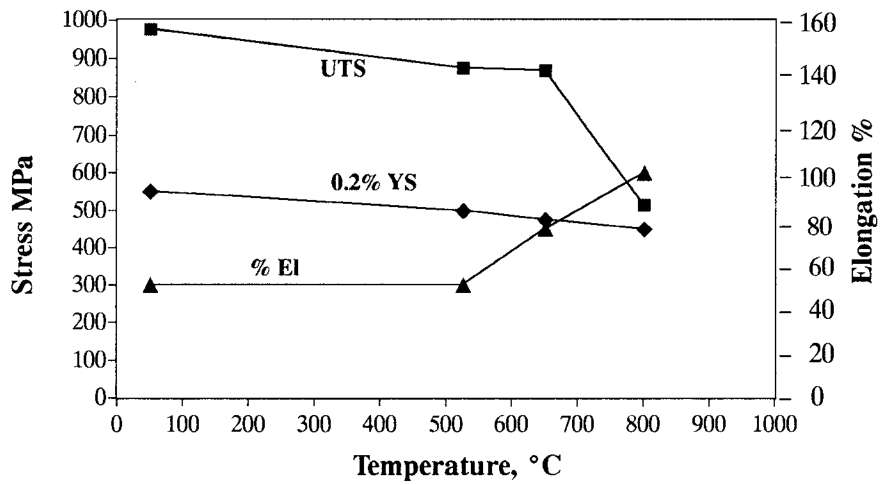

Figure 5. Tensile Properties to 816°C for VIM plus ESR Heat VX0057AK of alloy 625 Strip (0.15 mm gauge).

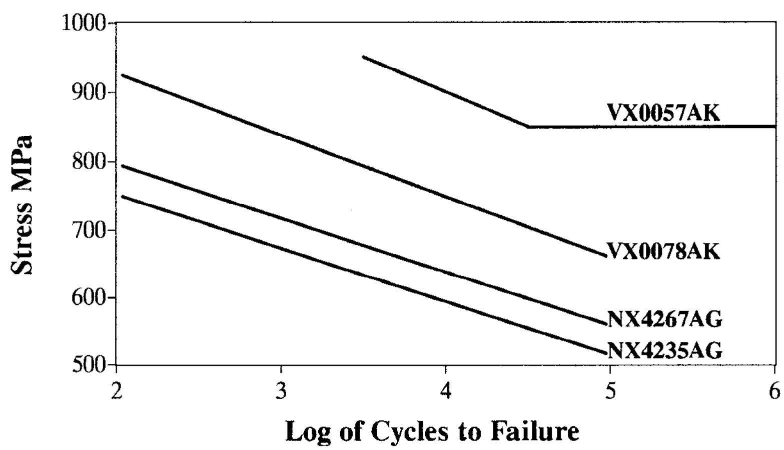

Figure 6. Stress controlled Tension–Tension LCF Properties at 538°C for Four Heats of Differing Composition and Method of Manufacture. Maximum Stress As Shown and Minimum Stress = 34.5 MPa. Test Frequency was 59 Hz and Wave Form Was Sinusoidal.

The difference in the amount of precipitated phases between the AOD plus ESR and the VIM plus ESR melt practice is shown in Table II.

Table II. Precipitated Phases in Annealed INCONEL alloy 625

Melt Method	Total Residue (Weight Percent)	(Nb, Ti) (C,N) (Weight Percent)	TiN (Weight Percent)
AOD Plus ESR (Heat NX4235AG)	0.38	0.30	0.08
VIM Plus ESR (Heat VX0057AK)	0.09	0.06	0.03

AOD Plus ESR Heat Contains 0.02% Carbon and 0.25% Silicon
VIM Plus ESR Heat Contains 0.01% Carbon and 0.06% Silicon

Because annealing practice is critical to establishing final grain size and mechanical properties, the effect of annealing temperature is illustrated in Table III for VIM plus ESR melted, hot rolled 15.9 mm diameter bar. The effect of elevated temperature exposure (300h at 593°C and 704°C) on LCF properties at 593°C is compared to as-annealed properties in Table IV. The effect of long term aging at 593°C, 649°C and 704°C on the stability of room temperature tensile properties of VIM plus ESR heats is shown in Tables V–VIII.

Table III – Anneal Response on Room Temperature Tensile Properties and Grain Size of VIM Plus ESR Hot Rolled 15.9 mm Diameter Bar

Annealing Conditions	0.2% Y.S. (MPa)	U.T.S. (MPa)	Elongation (%)	Grain Size (#)
Hot Rolled	929	1,114	38.0	12
927°C/30 min./AC	747	1,040	41.4	12
954°C/30 min./AC	586	1,004	46.0	11
982°C/30 min./AC	481	932	50.7	10
1038°C/30 min./AC	425	888	55.0	8
1066°C/30 min./AC	399	883	52.0	7
1093°C/30 min./AC	358	827	61.0	5

Heat VX0343AK: 0.01%C, 0.11%Si, 0.0003% N

Table IV – LCF Properties of VIM Plus ESR Strip at 593°C

Stress Controlled Tension–Tension Axial Mode Cycles to Failure			
Stress (MPa)	As-Annealed	Aged 593°C/300h	Aged 704°C/300h
758	600	10,100	18,756
690	14,500	69,928	99,021
621	300,000	> 10,000,000	> 17,000,000
552	1,900,000	> 10,000,000	> 10,000,000

Test Frequency: 59 Hz; Wave Form: Sinusoidal
Heat VX0078AK: 0.03% C, 0.11% Si, 0.011% N

Table V – Effect of Exposure at 593°C on Room Temperature Mechanical Properties

Hot Rolled and Annealed (982°C/30 min./AC) 38.1 mm Diameter Bar				
Property	As-Annealed	3 Months	6 Months	12 Months
0.2% Y.S. (MPa)	445	776	794	870
U.T.S. (MPa)	918	1,158	1,188	1,204
Elong. (%)	51.4	40.7	37.1	32.0
R. A. (%)	69.5	59.6	61.0	50.8
Charpy (joules)	>325	259	193	138

Heat VX0343AK: 0.01% C, 0.11% Si, 0.003% N

Table VI – Effect of Exposure at 649°C on Room Temperature Mechanical Properties

Hot Rolled and Annealed (982°C/30 min./AC) 38.1 mm Diameter Bar					
Property	As-Annealed	3 Months	6 Months	9 Months	12 Months
0.2% Y.S. (MPa)	445	945	925	908	910
U.T.S. (MPa)	918	1,258	1,258	1,261	1,276
Elong. (%)	51.4	28.0	24.0	25.7	25.0
R. A. (%)	69.5	47.0	43.0	41.7	34.9
Charpy (joules)	>325	71.0	41.0	-	25.8

Heat VX0343AK: 0.01% C, 0.11% Si, 0.003% N

Table VII – Effect of Exposure at 704°C on Room Temperature Mechanical Properties

Hot Rolled and Annealed (982°C/30 min./AC) 38.1 mm Diameter Bar				
Property	As-Annealed	3 Months	6 Months	12 Months
0.2% Y.S. (MPa)	445	712	798	807
U.T.S. (MPa)	918	1,119	1,144	1,110
Elong. (%)	51.4	26.4	-	17.0
R. A. (%)	69.5	29.8	-	17.8
Charpy (joules)	>325	28.0	26.0	15.0

Heat VX0343AK: 0.01% C, 0.11% Si, 0.003% N

Table VIII – Effect of Exposure at 649°C on Room Temperature
Mechanical Properties

Hot Rolled and Annealed (1066°C/5 min./AC) 0.84 mm Sheet					
Property	**As-Annealed**	**3 Months**	**6 Months**	**9 Months**	**12 Months**
0.2% Y.S. (MPa)	458	916	905	915	912
U.T.S. (MPa)	906	1,225	1,238	1,296	1,247
Elong. (%)	49.0	24.0	23.0	17.0	19.0
Hardness (Rc)	12	35	35	36	37

Heat VX0343AK: 0.01% C, 0.11% Si, 0.003% N

Discussion

Alloy 625 cold rolled and annealed sheet and strip is frequently manufactured to the composition of SAE AMS 5599C (revised 1984-10-01) using air melted, AOD processed and ESR material that is given a final anneal which results in a 0.020 mm gauge product with a 0.2% yield strength of less than 415 MPa and an ASTM grain size # of 8.0. One such heat, NX4235AG, is compositionally described in Table I, its tensile properties to 816°C are given in Figure 2 and its tension-tension LCF properties at 538°C in Figure 6. The total residue content (precipitates in the alloy in the as-annealed condition) is described in Table II. Contrasting this heat to subsequently described heats of higher purity and yield strength, it is noted in Table II that the product has the higher total residue content [particularly of (Nb,Ti)(C,N)] and the lowest LCF properties (Figure 6).

Heat NX4267AG (see Table I for composition) was melted and processed similarly to that of heat NX4235AG except that the final anneal was lowered to 1065°C from 1175°C, increasing the 0.2% yield strength to 530.2 MPa (ASTM grain size #9.0). The tensile properties to 816°C are given in Figure 3 and the tension-tension LCF properties in Figure 6. Increasing the yield strength marginally reduced room temperature ductility while elevated temperature ductility remained the same as that of heat NX4235AG. However, tension-tension LCF properties at 538°C were only modestly improved.

To reduce the inclusion content, a VIM plus ESR heat of alloy 625 was produced (VX0078AK) and processed into 0.20 mm gauge strip using the same manufacturing procedure as employed for heat NX4267AG. The composition of heat VX0078AK is given in Table I, its tensile properties to 816°C in Figure 4 and its tension-tension LCF properties at 538°C in Figure 6. While the tensile properties of this ASTM grain size # 9.5 heat are similar to those of heat NX4267AG, the LCF properties are markedly superior. At constant stress, the improvement in "cycles to failure" is approximately two log increments. This improvement in LCF behavior over heat NX4267AG is attributed mainly to product cleanliness as exemplified by heat VX0057AK described below. The compositional levels of carbon, silicon and nitrogen have clearly become important.

Heat VX0057AK was VIM plus ESR melted with compositional levels for carbon of 0.01%, for silicon of 0.06% and for nitrogen of 0.008%. Strip (0.15 mm gauge) was produced by the manufacturing method used for heat VX0078AK. Its tensile properties to 816°C are presented in Figure 5 and its tension-tension LCF properties at 538°C in Figure 6. The ASTM grain size # was 9.0. Tensile ductility was superior to that of heats NX4267AG and VX0078AK at both room and elevated temperatures and, as shown in Figure 6, tension-tension LCF properties were dramatically improved over previous heats. Table II suggests that product cleanliness was the major factor contributing to enhanced fatigue properties since grain size and yield strength were similar to that of the previously described heats. Enhanced ductility is not a principal factor accounting for the improvement in LCF properties since AOD plus ESR heat NX4235AG has similar but slightly lower ductility at 538°C.

Product cleanliness aids in insuring stability of mechanical properties after elevated temperature exposure. Table IV illustrates the retention and apparent enhancement of tension–tension LCF properties at elevated temperatures (data are presented for 593°C) following exposure at 593°C/300h and 704°C/300h. Retention of room temperature tensile and impact properties is also influenced by product cleanliness as shown in Table IV through VII. VIM plus ESR heat VX0343AK (composition as shown in Table I) was hot rolled to 38.1 mm diameter bar and annealed at 982°C/30 min./AC in a similar manner to the 15.9 mm diameter bar (Table III). The as-annealed bar was then aged for times to 10,800h (15 months) at 593°C (Table V), 649°C (Table VI) and 704°C (Table VII). The room temperature tensile properties and Charpy impact toughness were then measured. Excellent ductility and toughness retention are observed for exposures to 8,760h (12 months) at 593°C and to 6,480h (9 months) at 649°C. Satisfactory ductility and toughness retention is observed at 704°C to 10,800h (15 months). Similiarly, excellent ductility retention can be expected for sheet and strip as exemplified by Table VIII for exposure at 649°C for times up to 8760h (12 months). Table VIII presents room temperature tensile properties for cold rolled and annealed 0.84 mm gauge sheet.

The same factors that enhance resistance to mechanical fatigue also improve resistance to thermal fatigue. In a test involving thermal cycling between 150°C and 815°C, a VIM plus ESR heat of alloy 625 had a fatigue life of 21,376 cycles versus 16,012 cycles for an AOD plus ESR heat. Washer-shaped specimens 30.5 mm in diameter x 1.5 mm thick were held at the upper temperature for 11 minutes and at the lower temperature for one minute.

Because of the excellent performance of VIM plus ESR alloy 625 with controlled levels of, not to exceed, 0.03% carbon, 0.15% silicon and 0.02% nitrogen, it has been possible to obtain an aerospace material specification (SAE AMS-5879, issued 1991-01-01) for cold rolled and annealed sheet and strip to 2.54 mm gauge. This product has a minimum room temperature 0.2% yield strength of 414 MPa, at least 40% elongation, and a maximum grain size of ASTM # 5 or less depending on gauge.

Conclusions

(i) In this study, LCF properties are slightly improved in annealed alloy 625 strip by processing changes that increase yield strength.

(ii) Melt-controlled strip with restricted levels of silicon, carbon and nitrogen produces a cleaner microstructure with significant LCF strength enhancement.

(iii) Aging of melt-controlled strip at 593°C and 704°C/300h results in improved stress controlled tension-tension LCF properties.

(iv) Long-term (10,800h) exposure at 593°C, 649°C and 704°C results in a minimal degradation of room temperature ductility of annealed bar when carbon, silicon and nitrogen are controlled.