EFFECT OF HEAT-TREATMENT ON CREEP LIFE OF A NICKEL BASE ALLOY USED FOR LOW PRESSURE TURBINE BLADE IN A MILITARY AIRCRAFT ENGINE

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Abstract

Low Pressure Turbine (LPT) blade in a typical military aircraft engine gets exposed to a temperature in excess of 1000 K while rotating at 8500 rpm during maximum rating of the engine operation. Creep and fatigue are the major damage mechanisms limiting its life. Non-uniformity in combustion leads to development of hot spot causing local temperature rise in excess of 1200 K. Further, LPT rotor experiences over-speeding due to malfunction of the control system causing Low Cycle Fatigue (LCF) damage to the blade. Hence Stress Rupture Test (SRT) and Low Cycle Fatigue (LCF) are the life limiting tests for evaluation of a turbine blade material. Turbine blades of military aircraft engine are made of nickel base super alloys for their excellent high temperature resistance and its source of strengthening are γ' Ni_3 (Al, Ti) and carbides respectively. The size, shape and distribution of the strengthening phases can be modified following different heat-treatment cycle to optimise SRT and LCF life. This paper deals with the effect of two heat-treatment cycles on SRT life of a wrought nickel base alloy having major alloying elements as Co, Cr, W, Mo, Al and Ti etc. The two types of heat-treatment cycles are as follows:Type I, Solutioning - Heating at 1220° C for 4 hours followed by cooling in air. Further heating to 1050°C soaking for 4 hours and cooling in air. Ageing cycle comprises of heating at 950°C for 2 hours followed by cooling in air. Type II, Solutioning - Heating at 1210°C for 5 hours and then transferring to a furnace at 1050°C soaking for 1/2-3/4 hour followed by cooling in air. Ageing cycle consists of heating at 900°C soaking for 12 hours followed by cooling in air. Fractography on the tested samples to arrive at the mode of failure, characterisation of the microstructure in respect of γ' Ni_3 (Al, Ti) and carbides using optical microscopy and SEM have been carried out to relate with the SRT life.

Introduction

Development of military aircraft engines is dictated by higher thrust that could be achieved by increasing TET (Turbine Entry Temperature), however, it is limited by the high temperature capability of the material. Life of turbine blade is determined by its resistance to creep and stress rupture. Nickel base super alloys are being used for turbine blades for its excellent high temperature strength, resistance to oxidation and corrosion and last but not least the manufacturability [1]. Nickel base alloys consists of a FCC matrix of gamma γ with strengthening phases of gamma prime γ'(Ni_3(Al,Ti)) and secondary carbides. Carbides present along grain boundary prevent slipping of grains, thereby providing resistance against creep for the alloy[2]. The primary design criteria for turbine blade are creep/stress rupture and LCF (Low Cycle Fatigue) life while secondary requirements are corrosion and high temperature oxidation [3]. Blade material selection is dictated by primary requirements while secondary requirement is met by providing suitable coating. Turbine blades of 2nd generation aero-engines are generally made of wrought nickel base alloys.

There was a premature failure of turbine blade attributed to fatigue with initiation at carbides and subsequent test on the material reveal poor SRT(Stress Rupture Test) life. Further literature reveals that there are different cycles for qualifying the billet and forging. This study has been taken to evaluate the effect of heat-treatment and forging process on the SRT life, which is the acceptance criterion for the blade. This study deals with a Russian origin wrought nickel base super alloy AP220BD used for manufacturing LPT (Low Pressure Turbine) blade of a typical straight flow twin spool turbojet engine having TET of 1130°C. The turbine blade rotates at 8500 rpm with an upstream gas temperature of 900°C and downstream gas temperature of 840°C during its operation.

Metallurgy of the Alloy

AP220 BD is a wrought Nickel base super alloy used for manufacturing turbine blade by forging route. The major alloying elements are Co, Cr, Mo, W, Ti and Al amounting to approximately 45%. The chemical composition of the alloy is placed at Table-1 [4,5]. Table-2 renders some details of mechanical properties of the alloy.The alloy in the form of cold rolled and annealed condition is used as a feed stock for the forging. As a part of qualification of billet, prior to forging, the material is subjected to solutionising and annealing for mechanical test both at RT (Room Temperature) and elevated temperature. The heat treatment cycle for the billet is as follows: Solutioning - Heating at 1220°C for 4 hours followed by cooling in air, and further heating to 1050°C soaking for 4 hours and cooling in air. Ageing cycle comprises of heating at 950°C for 2 hours followed by cooling in air.

Formation of Carbides and Strengthening Mechanism in Nickel Alloy

Nickel-based super alloys are basically nickel-chrome alloys with a face-centered cubic solid-solution matrix containing carbides and coherent intermetallic precipitate $Ni_3(Al, Ti)$.Wrought and age-hardenable nickel-based superalloy, is strengthened by the addition of titanium, aluminium, carbon and the stress-rupture properties is strongly dependent on microstructure features such as grain size, grain boundary precipitates such as carbides and their distribution, volume fraction, size and distribution of gamma prime γ' in the matrix. The precipitate of ordered phase γ' provides most of the alloys with high temperature strength and long term stability. The development of nickel-based superalloy requires a quantitative determination of the parameters of the super alloys structure, one of them is the lattice misfit δ between the γ and γ' phases [6],

$$\delta = \frac{2\,(a\,\gamma' - a\,\gamma)}{a\,\gamma' - a\,\gamma} \tag{1}$$

where a γ' and a γ are the lattice parameters of the γ' and γ phases, respectively.

Table-1 : Chemical Composition

Ni	Co	Cr	Mo	W	Ti	A1	V	Fe	C	Mn	Si	S
Base	14-16	9-12	5-8	5-7	2.2-2.9	3.9-4.8	0.2-0.8	3 Max	0.08 Max	0.5 Max	0.5 Max	0.004 Max

Table-2 : Mechanical Properties

Properties	UTS MPa	YS MPa	% EL	% RA	Young's Modulus MPa	Stress Rupture Test		
						Stress MPa	Temp °C	Life (Hr)
RT	112.55	77.15	20.30	17.30	212.82	28	900	50 Min

Three types of carbides, MC, M_6C and $M_{23}C_6$, are observed having MC the most refractory carbide. Each type of carbides has a different stable temperature range, which indicates the relative stability of carbides. MC carbide is stable from 850 to 950°C; M_6C carbide is most stable above 1000°C; $M_{23}C_6$ carbide appears in the 950-1000°C temperature range. The rate of MC decomposition increases with the increase of thermal exposure temperature. Some M_6C carbide particles which are transformed from MC carbide particles adhere irregularly to the original MC carbide; the other M_6C carbide precipitates are needle-shaped, globular, cubic and blocky. Furthermore, needle-shaped M_6C carbide is the most prevalent and has the coherent relationship with the matrix. M_6C and script like MC carbide particles are detrimental to room temperature tensile and stress rupture properties. The globular $M_{23}C_6$ particles are precipitated in grain boundaries, but have little effect on the properties of the alloy because of their rare presence [7,8,9].

Enhancement of the high temperature performance of wrought nickel base super alloys has been explored via processing/heat treatment in order to develop optimum microstructures for creep resistance. The matrix grains, γ' precipitates, and grain boundary carbides are the key features. The optimum grain size is generally obtained by solution treatment at temperatures in the range 1000-1220°C. The γ' precipitates and the grain boundary carbides are produced during subsequent aging treatment at 700-900°C. Grain boundary carbides present in 'blocky' form as discrete particles lead to strengthening of nickel base superalloys owing to the pinning of grain boundaries, and the inhibition of grain boundary sliding and migration. Grain boundary carbides with continuous morphology, however, can have a detrimental effect on the creep properties. These types of carbide have been shown to provide an easy path for crack propagation. The morphology of grain boundary carbides is usually related to the alloy chemistry and/or the heat treatment [10].

Forging of Blade

Nickel base alloys are strain rate sensitive as well as structure sensitive. Basically critical grain growth rate and over solutioning of γ' are the factors need to be considered during forging of blade. The microstructure control of γ' and carbide is generally associated with working below the solutionising temperature of the γ'. Forging and subsequent heat-treatment temperature are selected and controlled according to the γ' solutionising temperature and the carbide reactions which take place above and within the γ' precipitation range [11].

The forging process consists of upsetting, pre-stamping, final stamping, coining and trimming which was shown in form of a flow chart at Fig.1. The primary manufacturing route for the turbine blade is envelope forging while the finished shape of the aerofoil profile is made by non-conventional machining route ECM (Electro Chemical Machining) and fir-tree of the blade root by broaching. The steps in the forging process consists of upsetting followed by pre-stamping, final stamping, coining and finally trimming which was shown in a flow chart in Fig.1. The forging is made using a 4000 Tonne press with the maximum deformation of approximately 50%. The feed stock used for forging is in hot rolled condition with a bar diameter of Φ35mm. The bar stock is subjected to immersion ultrasonic for absence of flaw with a sensitivity of FBH(Flat Bottom Hole) 1mm. The forged blades are subjected to solutionising and aging prior to machining. Solutioning - Heating at 1210°C for 5 hours and then transferring to a furnace at 1050°C soaking for 1/2-3/4 hour followed by cooling in air. Ageing cycle consists of heating at 900°C soaking for 12 hours followed by cooling in air [12].

Experimental Detail

SRT(Stress Rupture Test) specimens were prepared from billet of Φ35mm along longitudinal direction. Also specimens were prepared from quarter section of the billet simulating the C_{max} thickness of blade. A sketch of the SRT specimen having a gauge diameter of Φ5mm and gage length of 25mm following GOST:10145 [13] is placed at Fig.2 The test is carried out using the ATS Inc, USA machine of capacity 2000kg at a stress (σ) of 28 kg/mm^2 at 900°C and at a stress of 31 kg/mm^2 at 900°C for the billets undergoing Type-I and Type-II heat-treatments respectively. The temperature is measured and controlled with an accuracy of ±2°C by placing a K-type chromel-alumel thermocouple at the middle of the specimen.

Specimens have been taken along longitudinal and transverse section near fracture and away from fracture to correlate the properties with microstructure. Optical microscope of make: Leica has been used to reveal the microstructure wrt grain size, secondary carbides etc. The etchant used was consists of $FeCl_3$, $SnCl_2$, HCl and water. Fractographic studies have been carried out both at lower magnification using stereo-microscope and at higher magnification with the help SEM.

Results and Discussion

The chemical composition for carbon, titanium and aluminium and stress rupture test results have been tabulated in Table-3. Particularly, the carbon, titanium and aluminium affect most the stress rupture life [14,15]. Carbon content being found to be same in all the four batches (Table-3), ratio of Ti/Al has been computed and its effect on rupture life has been plotted in Fig.3 [16]. The average rupture life under Type-I heat-treatment is 70hr while for Type-II H/T is 43 hr. Though, no definite trend is found in Ti/Al ratio on rupture life, there is a point beyond which it stabilises. However, more tests may be required to establish the trend. LM (Larson Miller) Parameter has been calculated and plotted against applied stress at Fig.4. The microstructure of billet, post heat-treatment, and forging+ H/T are placed in Fig.5(a), (b) and (c).

Fractographs of specimen having maximum and minimum life in stress rupture test have been compared in Fig.6(a) and (b). The grain size near fracture and in the gripped region has been measured with an image analyser and the results are tabulated in Table-4. The average grain size is found to be approximately 388 µm and 379 µm respectively with an average grain size of 210 µm for the specimen having maximum life while for the billet giving lowest life, it is found to be 363 µm and 345 µm respectively with an average grain size of 155 µm. Further SEM study reveals that, the strengthening phase Υ' having cuboidal shape shown in Fig.7(a) provides higher resistance, thereby more life, whereas, the specimen having coarser/elongated γ' shown in Fig.7(b) yields less life. Hence, the large variation in life is attributed to grain size variation and coarsening of γ' on the billet. Fractographic study reveals IG (Inter Granular) mode of fracture placed in Fig.8(a) and (b) which is the major damage mechanism operative during elevated temperature testing [17]. Carbide stringers found in the billet in Fig.5(c) act as an inclusion which may drastically deteriorate the mechanical properties. Hence, forging process need to be devised in such a way that, carbide stringers get broken, thereby improving the mechanical properties.

Table-3 : Stress Rupture Test Data

Batch No.	Carbon	Ti	Al	H/T Cycle	Test Temperature (C)	Stress (kg/mm^2)	Rupture Life (Hr)
A	0.04	2.50	4.02	Type-I	900	28	68
				Type-II	900	31	40
B	0.04	2.49	4.01	Type-I	900	28	66
				Type-II	900	31	36
C	0.04	2.78	4.24	Type-I	900	28	85
				Type-II	900	31	45
D	0.04	2.53	4.03	Type-I	900	28	44
				Type-II	900	31	33

Table-4 : Comparison of Grain Size

	Gripping Region	Gauge Portion	Gripping Region	Gauge Portion
	Highest Life		Lowest Life	
Grain Size µm	379	388	363	345
Average Grain Size µm	≈ 210		≈ 155	

Conclusions

Following conclusions can be made from the study:

- Prior grain size dictates the stress rupture property of the billet. The coarser the grain, higher the rupture life.

- Ratio of Ti/Al influences the stress rupture life and there is a point beyond, life stabilises.
- Deformation followed by solutioniisng and aging could yield highest stress rupture life. Either of these alone could not yield the superior life against stress rupture.
- Presence of carbide stringers deteriorate the rupture life and thereby need to be broken down during forging operation.

Acknowledgement

The authors acknowledge the support and encouragement rendered by Chief Executive (Airworthiness) and Group Director (Propulsion), CEMILAC, Bangalore for the publication of this work. The support rendered by Director, Defence Metallurgical Research Laboratory (DMRL), Hyderabad is also greatly acknowledged.

References

1. Donachie Mathew., Donachie, J. and Stephen Mathew., " Superalloys A Technical Guide", ASM International, The Material Information Society, Chapter-12, 2002, pp.211-259.

2. Sims, C.T., "The Superalloys Wiley Interscience", 1972.

3. Reed, C. Roger., "The Superalloys - Fundamentans and Applications", Cambridge University Press, 2006.

4. Russian Specification, Ty:14-1-223-72.

5. Khimishuin, F. F., "High Temperature Steels and Alloys", Foreign Technology Division, Wright Patterson, AFB, Ohio, Chap-1.

6. Chakravorty, S., West, D. R. F., "High Temperature Strength of Nickel Alloys Based on γ' Phase", Metals Technology, October, 1980, pp.414-419.

7. Hammond, C. and Nutting, J., "The Physical Metallurgy of Super Alloys and Titanium Alloys", Metal Science, October, 1977, p.476

8. Youdelis, W.V. and Known, O., "Carbide Phases in Nickelbase Superalloy : Nucleation Properties of MC Type Carbides", Material Science, Vol.17, 1985, pp.385-388.

9. Yang, Jinija., and Zheng, Qi, et al., "Relative Stability of Carbides and Their Effect on the Properties of K465 Superalloy", Material Science and Engineering, A429, 2006, pp.341-347.

10. Pandey, M. C., Satyanarayan, D. V. V. and Tapline, D. M. R., "Performance Enhancement of Alloy X-750 During Creep via Optimal Solution Treatment and Control of Morphology of Grain Boundary Carbide", Material Science and Technology, Vol.10, November, 1994, pp.936-939.

11. Coyne, J. E., "Microstructure Control in Titanium and Nickel Base Forging", Metals Technology, July, 1977, pp.337-345.

12. Blade Manufacturing Technology, 55MP-81.

13. Stress Rupture Test Standard, GOST:10145.

14. Liu, L. R., Jin, T., Zhao, N. R., San, F. R., Guan, H. R. and Hu, Z. Q., "Formation of Carbides and Their Effect on Stress Rupture of a Ni-base Single Crystal Alloy", Material Science and Engineering, A-361, 2003, pp.191-197.

15. Yulai Xu., Qiumin Jin., Xueshan Xiao., Xiuli Cao., Guoqing Jia., Yuemei Zhu and Huaijin Yin., "Strengthening Mechanisms of Carbon in Modified Nickel-Based Superalloy Nimonic 80A", Material Science and Engineering, A-528, 2011, pp.4600-4607.

16. Yulai Xu., Lei Zhang., Jun Li., Xueshan Xiao., Xiuli Caob., Guoqing Jia and Zhi Shen., "Relationship Between Ti/Al Ratio and stress-Rupture Properties in Nickel-Based Superalloy", Material Science and Engineering, A-544, 2008, pp.48-53.

17. Joy Mittra, A. N., Suparna Banerjee., Raghvendra Tewari and Gautam K. Dey., "Fracture Behavior of Alloy 625 with Different Precipitate Microstructures", Material Science and Engineering, A-574, 2013, pp.86-93.

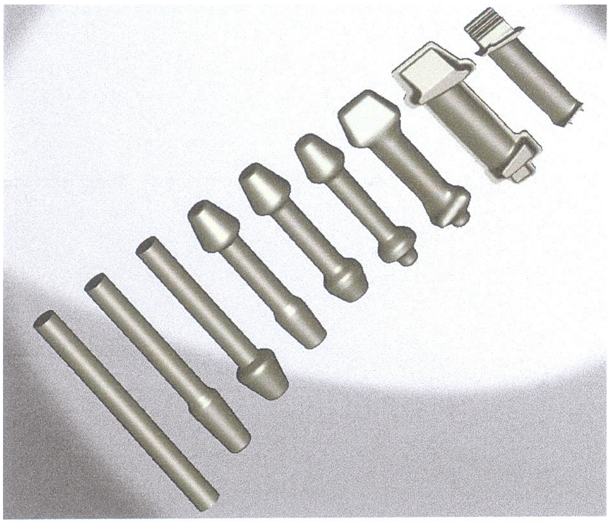


Fig.1 Flow Chart-Blade Manufacturing

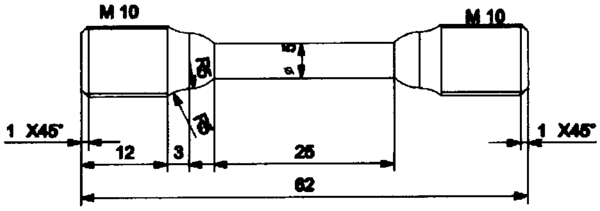


Fig.2 Dimensions of SRT Specimen

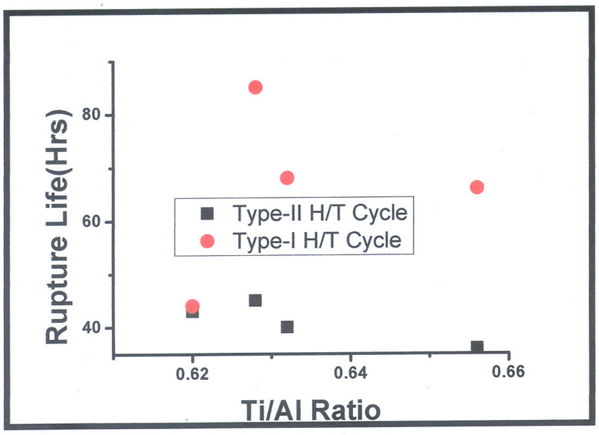


Fig.3 Rupture Time Vs Ti/Al Ratio

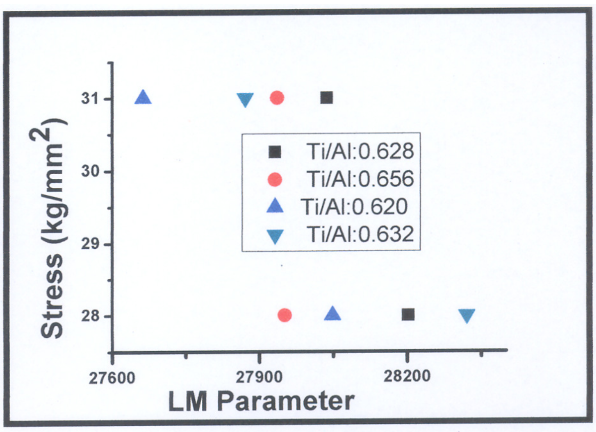


Fig.4 Larson Miller Parameter Plot

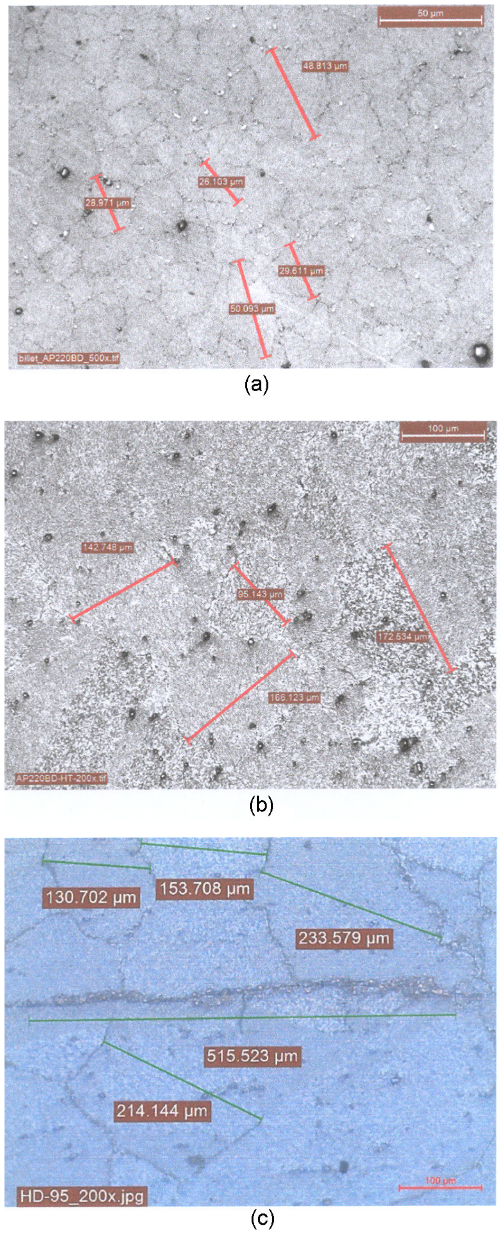
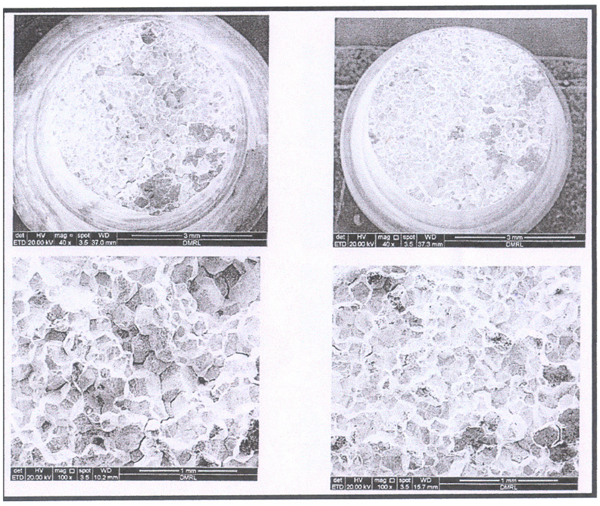
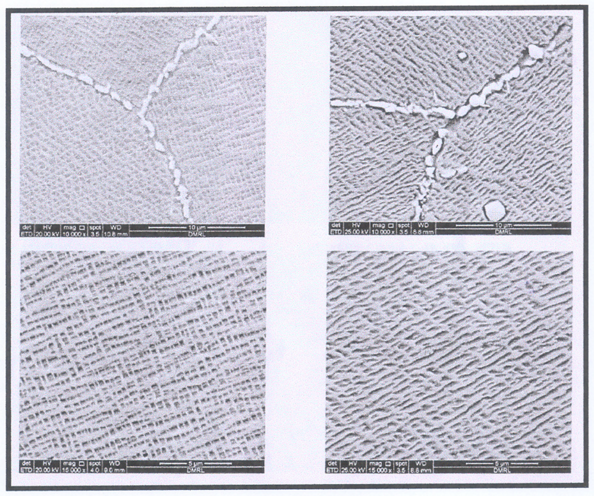


Fig.5 Microstructure with Grain Size (a) Billet (b) Billet with Heat Treatment (c) Forging with Heat Treatment



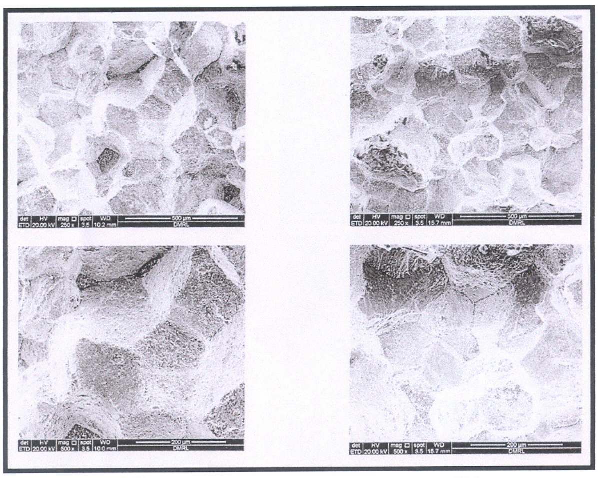
(a) (b)

Fig.6 Fractographs of SRT Fractured Specimen
(a) Highest SRT Life, (b) Lowest SRT Life



(a) (b)

Fig.7 Micrographs with SEM
(a) Highest SRT Life - Cuboidal ϒ’
(b) Lowest SRT Life - Elongated/Coarse ϒ’



(a) (b)

Fig.8 Fractograph with SEM
(a) Highest SRT Life - Intergranular Fracture
(b) Lowest SRT Life - Intergranular Fracture