NASA
Contractor Report 175052

USAAVSCOM
Technical Report 86-C-14

Axial and Torsional Fatigue Behavior of Waspaloy

S. Zamrik, M. Mirdamadi, and F. Zahiri
The Pennsylvania State University
University Park, Pennsylvania

April 1986

Prepared for
Lewis Research Center
Under Grant NAG 3-264

National Aeronautics and
Space Administration

U.S. ARMY AVIATION SYSTEMS COMMAND

AXIAL AND TORSIONAL FATIGUE BEHAVIOR OF WASPALOY

S. Zamrik, M. Mirdamadi, and F. Zahiri
The Pennsylvania State University
Engineering Science and Mechanics Department
University Park, Pennsylvania 16802

INTRODUCTION

This is a brief progress report describing the failure modes observed in completed cyclic and hold-time tests conducted on Waspaloy material at 1200 °F. The Waspaloy material was made of two grain structures, identified as fine grain (16 μm) and coarse grain (124 μm). The material has γ' precipitates of two sizes, one small (50 Å) associated with coarse grain and one large (1000 Å) associated with fine grain.

TESTS CONDUCTED

Axial and torsional cyclic tests were completed on the two types of grained structure at room temperature and 1200 °F. Also hold-time tests with 90 sec hold in the tension side of the axial loading and in the counterclockwise side of the torsional loading. The type of wave shape that was applied is shown on the individual macrograph.

LOW-CYCLE FATIGUE TORSIONAL TESTS (COARSE GRAIN)

Figure 1 shows the failure mode of a coarse grained test specimen that failed under torsional shear strain range continuous cycling at 1200 °F. The failure mode shows a transition from shear observed at room temperature to tensile stage at 1200 °F. To verify this 45° crack mode, duplicate tests were conducted at two levels of plastic shear strain ranges, one at $\Delta\gamma_p$ = 0.52 percent to failure and the other at $\Delta\gamma_p$ = 92 percent to failure. In both cases, the failure mode was tensile with cracks at 45° mode as shown in figure 2.

Microscopic examination was conducted using replicas and scanning electron microscopy techniques. Figure 3 shows the general cracking path at

45° with respect to specimen axis. The zigzagging crack path shown in figure 3(b) was studied with an enlargement shown in figure 3(b). The progress of the crack was hindered by grains that saw little plastic deformation (slip bands activities) and were in elastic condition forcing the crack to deviate. This is shown clearly in figure 3(c). Furthermore, at 1200 °F, carbides and precipitates were observed on slip bands and on grain boundaries as shown in figure 3(e). Therefore, the tensile failure mode can be attributed to the embrittlement of these carbides, assisted by an oxidation that enhanced the embrittlement process. Embrittled regions are sensitive to normal stresses. Figure 3(e) also shows additional large particles. The chemical composition of these large particles was found, by x-ray energy spectrum analysis (fig. 4), to be the same material as that of the matrix. These large particles have also initiated crack sites that contributed to mode I cracking. With respect to the slip mode characteristic, it was found in all cases to be planar slip that resulted in γ' particles shearing.

TORSIONAL HOLD-TIME TEST (COARSE GRAIN)

The test at 1200 °F under 90 sec hold time showed similar failure characteristics (45°) to that observed under continuous cyclic with little effect of creep as shown in figure 5. Replicas taken on the surface after failure showed extensive grain boundary cracking, planar slip and some twinning as shown in figure 6. Also observed, an extensive oxidation on slip bands and grain boundaries. In general, the microscopic behavior of the hold-time test was similar to that under continuous cyclic except for the amount of oxidation. The crack growth was also at 45° with respect to specimen axis.

AXIAL HOLD-TIME TEST (COARSE GRAIN)

The axial hold-time test at 1200 °F, showed the failure to be normal to the loading axis as shown in figure 7. Scanning electron microscopy analysis of the gauge surface, figures 8 and 9, showed mixed ode crack initiation: grain boundary cracking and slip band cracking. However, the propagation was mostly transgranular.

Microscopic comparison between the axial and torsional hold-time failure characteristics, revealed extensive multiple slip system activity as well as twinning to have taken place in the axial case. Also the axial case showed a greater grain boundary cracking. The creep effect was observed to be minimum.

TORSION HOLD-TIME TEST (FINE GRAIN)

The torsional hold-time test of the fine grained specimen resulted in a shear mode failure (longitudinal crack along specimen axis) as shown in figure 10. The microscopic examination of the gauge surface showed extensive grain boundary oxidation and some grain boundary cracking that resulted in inter- and transgranular crack growth. Ill defined oxidized wavy slip bands (fig. 11), were observed rather than the strict planar slip that was seen in other described tests. Replicas taken on the surface are shown in figure 12. Creep showed an effect when compared to data obtained on coarse grain test.

AXIAL HOLD TIME (FINE GRAIN)

The axial hold-time test of the fine grained specimen showed the failure to be normal to the loading axis as shown in figure 13. The microscopic examination of the gauge surface showed extensive grain boundary cracking, wavy slip and considerable oxidation. These features are shown in figures 14 and 15. The comparison between the torsional and the axial hold-time tests of the fine grained specimen showed distinct features:

(1) The axial hold time produced excessive grain boundary cracking.

(2) The torsional hold time showed excessive oxidation and less grain boundary cracking.

(3) Creep effect was greater in the axial case.

CYCLIC STRESS-STRAIN RESPONSE

Hysteresis loops for both types of axial and torsional hold time taken at half lives are included in figures 16 to 20. The variation in the shear stress range for the case of continuous shear strain cycling at room and 1200 °F shows an interesting behavior for each type of grained specimen on a cycle basis. The fine grained material exhibited substantial stress relaxation during the 90 sec hold time under both axial and torsional loading, as may be seen in figures 16 and 17. The 90 sec strain hold resulted in about 25 percent stress relaxation in both cases: for torsional loading, the cyclic stress amplitude was about 48 ksi, with 12 ksi relaxation during the hold. Similarly, under axial loading the cyclic amplitude was 104 ksi, with 22.4 ksi relaxation after the 90 sec strain hold.

In comparison, the coarse grained material showed very little stress relaxation after 90 sec strain hold, as may be seen in figures 18 and 19. This is partly due to the softer (lower peak cyclic stresses) condition of the coarse grain material. Also, if time dependent deformation occurs predominantly at grain boundaries, the coarse grain material would afford a reduced opportunity for time dependent deformation to occur.

The torsional cyclic stress-strain behavior of both the fine grain and coarse grain material is summarized in figure 20. The fine grain material shows substantial hardening (about 10 percent increase over initial cyclic stress range) up to 10 to 20 percent of life, followed by softening out to failure. This behavior was exhibited at both room temperature and 1200 °F. The coarse grain Waspaloy on the other hand, showed either a flat response at room temperature, or monotonic softening at 1200 °F.

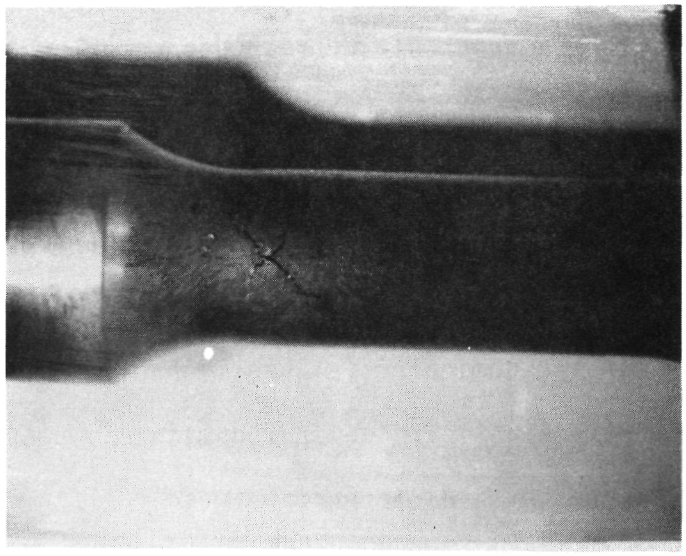
CONCLUSIONS

(1) There appears to be reasonable correspondence between axial and torsional low-cycle fatigue (LCF) in fine grained Waspaloy tested at both 75 and 1200 °F.

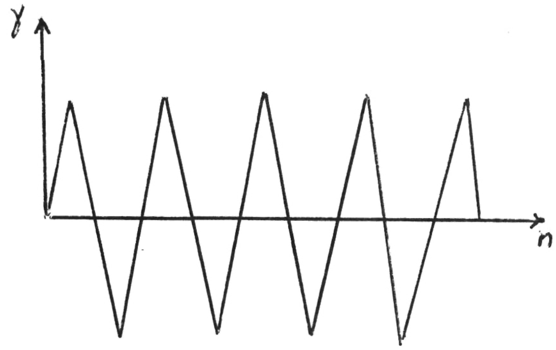
(2) There is also reasonable correspondence between the damage mechanisms observed in axial and torsional LCF in coarse grained Waspaloy at 75 °F. However, at 1200 °F a tensile dominated failure mechanism was activated in torsional loading whereas a plasticity dominated mechanism was activated in axial loading. Also, there was a difference between the fine grained and coarse grained Waspaloy damage mechanisms at 1200 °F.

(3) During cyclic hold-time experiments, fine grain Waspaloy demonstrated substantial stress relaxation at 1200 °F, under both axial and torsional loading. Very little relaxation was observed in coarse grain Waspaloy. Also, cyclic hardening was observed in fine grain Waspaloy at both room temperature and 1200 °F; coarse grain Waspaloy exhibited either flat cyclic response or monotonic softening.

(4) These experiments demonstrate that LCF damage depends on the material and heat treatment, the test temperature and the state-of-stress.



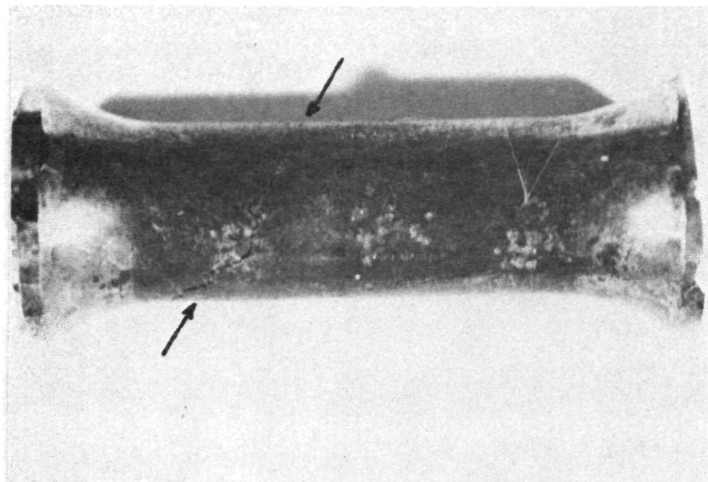
(a)



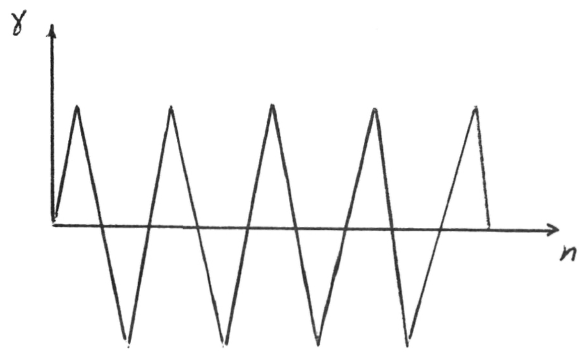
(b)

Fig. 1 a) Macrophoto of Waspaloy course grain torsional 1200°F. (Spec. BF27, $\Delta\gamma_T$=1.58%, $\Delta\gamma_P$=0.65% @ $N_f/2$, N_f=4528) Note primary cracking at 45° to specimen axis on planes of maximum tensile stress.

b) Applied wave form (10 cpm).



(a)

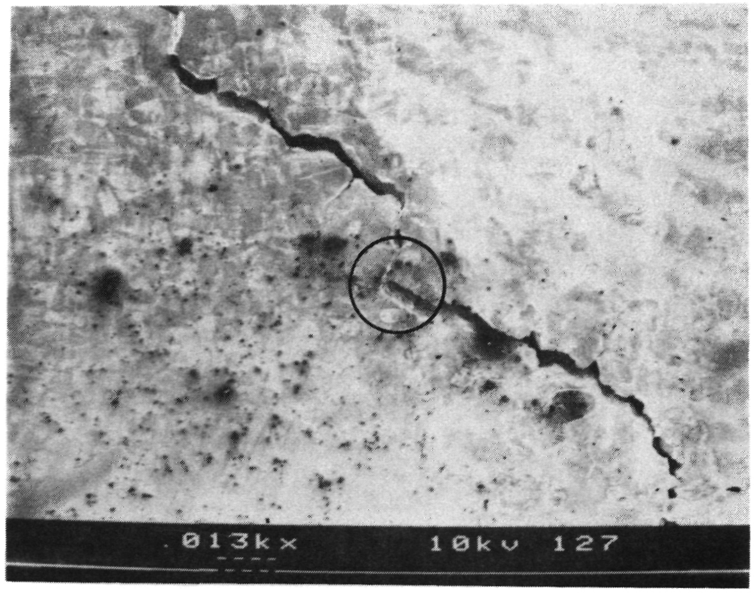


(b)

Fig. 2 a) Macrophoto of Waspaloy course grain torsional 1200°F. (Spec. BF4, $\Delta\gamma_T$=1.34%, $\Delta\gamma_P$=0.52% to failure, N_f=5500) Note primary cracking at 45° to specimen axis on planes maximum tensile stress.

b) Applied wave form (10 cpm).

SPEC. AXIS



(a)

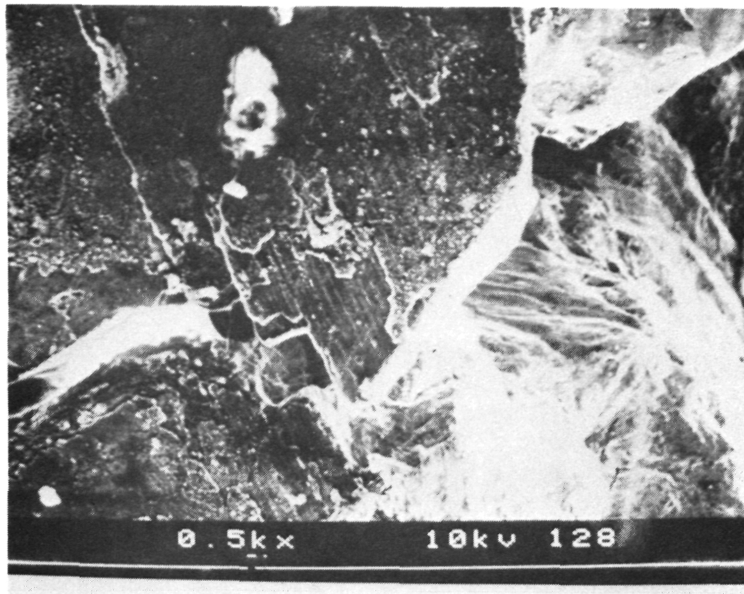
SPEC. AXIS

(b)

Fig. 3 a) Primary crack at 45° to the specimen axis (Spec. BF4) on planes of maximum tensile stress.

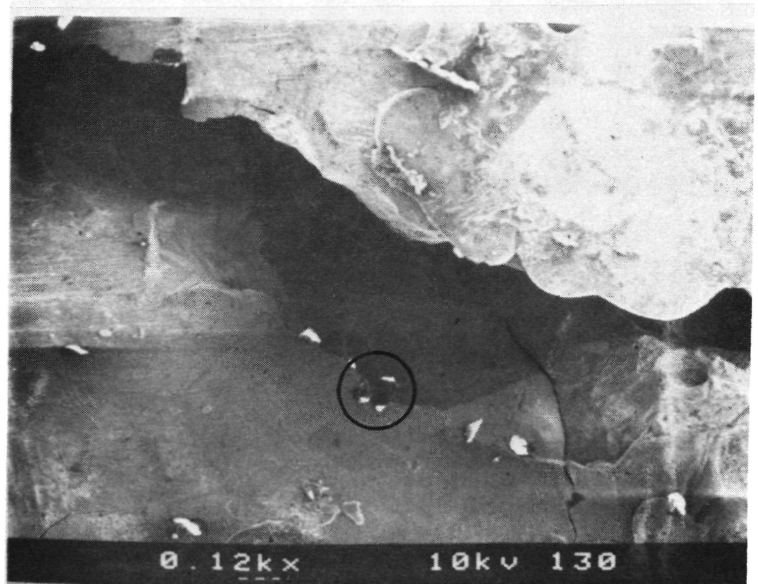
b) Enlarged region of (a) showing slip band formation and crack orientation and propagation. It also shows undeformed grain ahead of the crack front forcing the crack to change direction.

SPEC. AXIS ⟵ ⟶



(c)

SPEC. AXIS ⟵ ⟶



(d)

Fig. 3 c) Enlarged region of (b), showing further details of the crack arrest and orientation.

d) Micrograph showing the major crack was due to large particles (inclusions) in the grain.

SPEC. AXIS

(e)

Fig. 3) Micrograph showing the crack was initiated on the maximum tensile stress and propagated at 45^{o} to the slip bands, Mode I crack propagation. Note large particle formation.

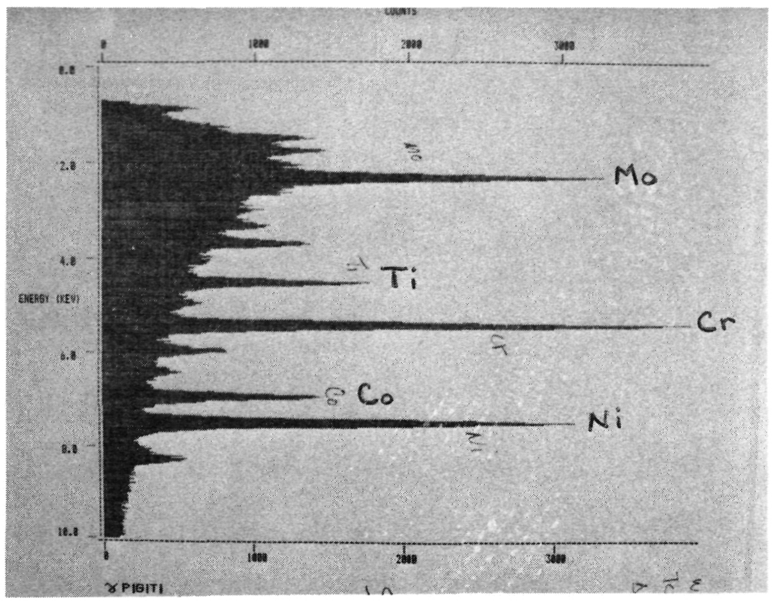
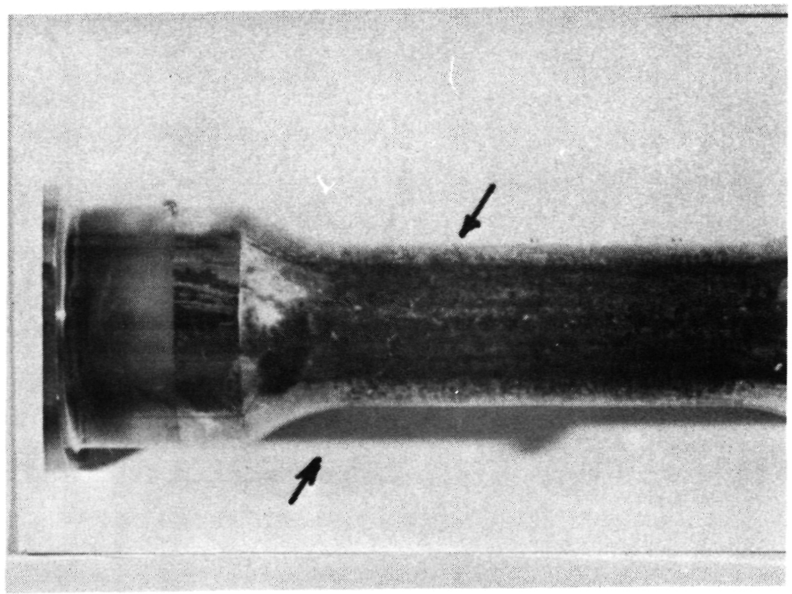
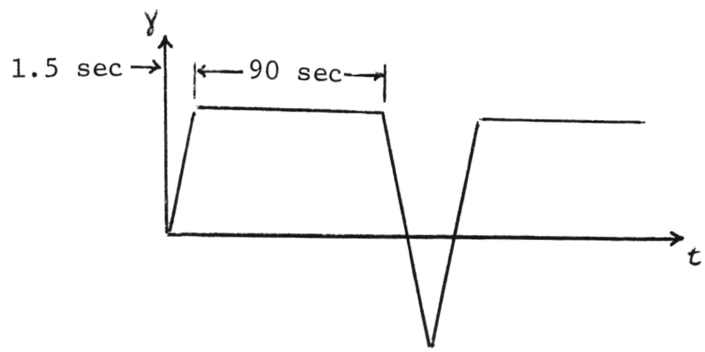


Fig. 4) X-Ray energy spectrum analysis revealed the content of the particles (inclusions) to be Ni, Cr, Mo, Co, Ti.



(a)

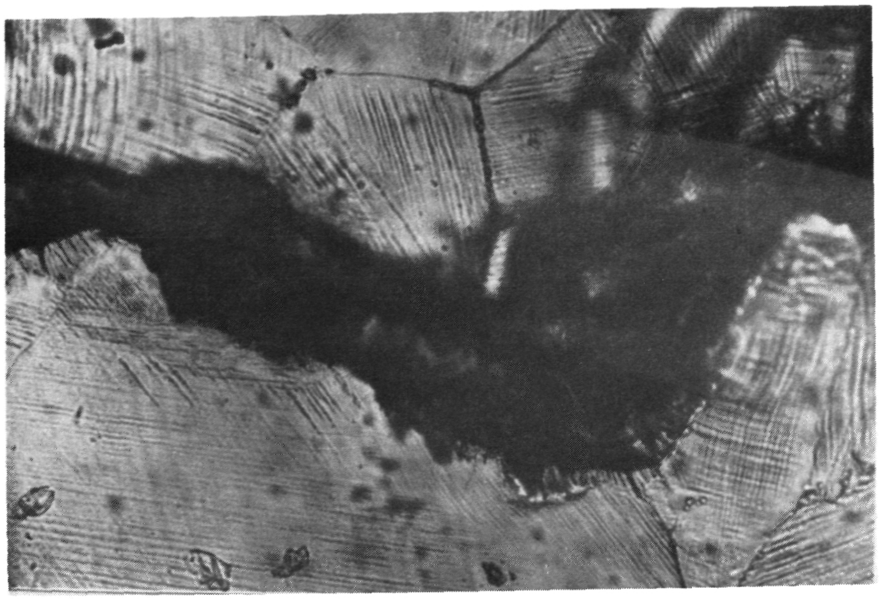


(b)

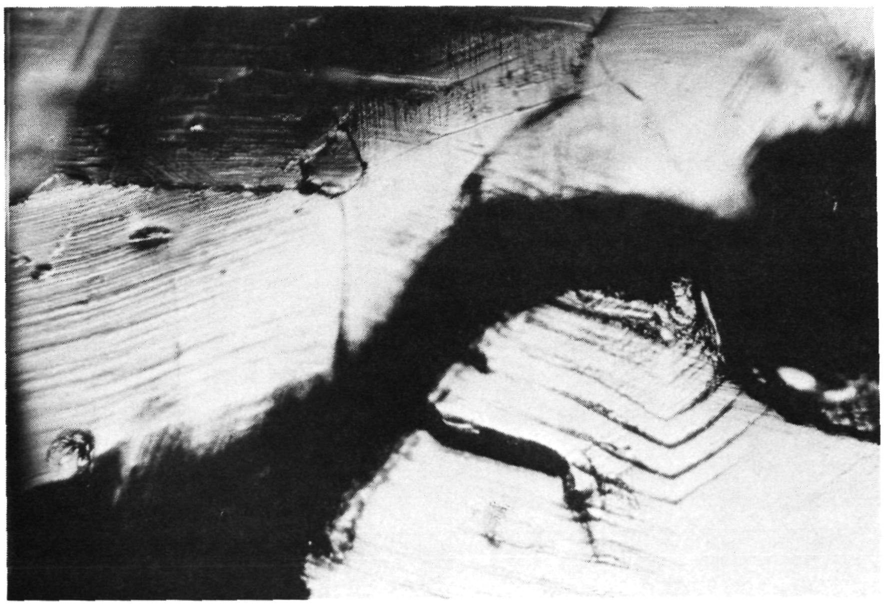
Fig. 5 a) Macrophoto of Waspaloy course grain: Torsion with hold time. (Spec. BF25, $\Delta\gamma_T$=1.55%, $\Delta\gamma_{in}$=0.643% @ $N_f/2$, N_f=2691, T=1200°F, t=90 Sec.) Note primary crack at 45° to the specimen axis on plane of maximum tensile stress.

b) Applied wave form.

SPEC. AXIS

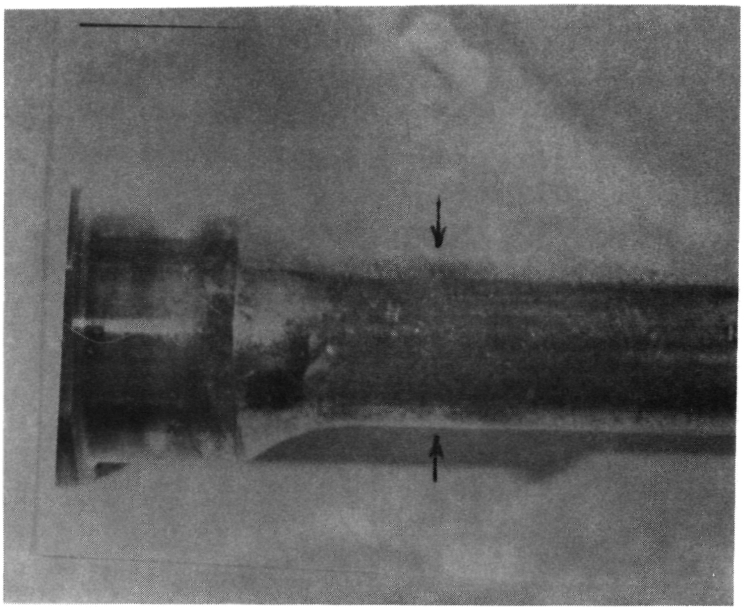


(a)

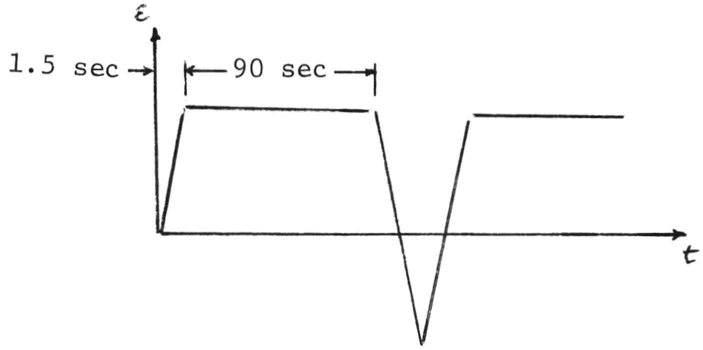


(b)

Fig. 6 a,b) Replicas of gage surface along the major crack at 40X. Mixed mode cracking is shown, grain boundary cracking, twining deformation, multiple slip system are observed.



(a)

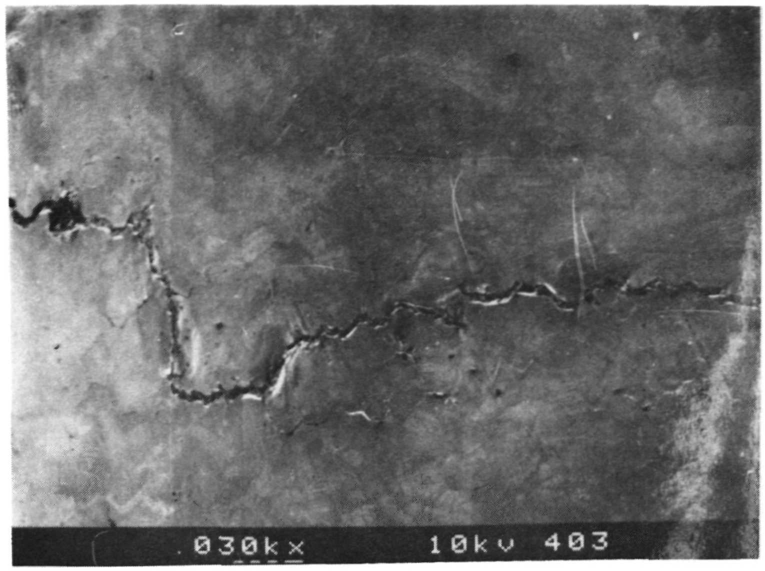


(b)

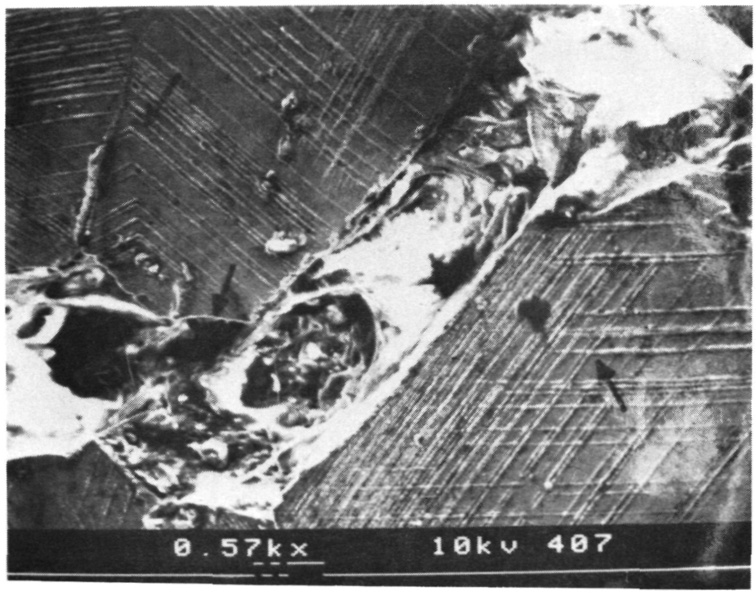
Fig. 7 a) Macrophoto of Waspaloy course grain: Axial with hold time. (Spec. BF8, $\Delta\varepsilon_T$=0.7%, $\Delta\varepsilon_{in}$=0.29% @ $N_f/2$, N_f=987, T=1200°F, t=90 Sec.) Note primary crack normal to the loading axis.

b) Applied wave form.

SPEC. AXIS



(a)

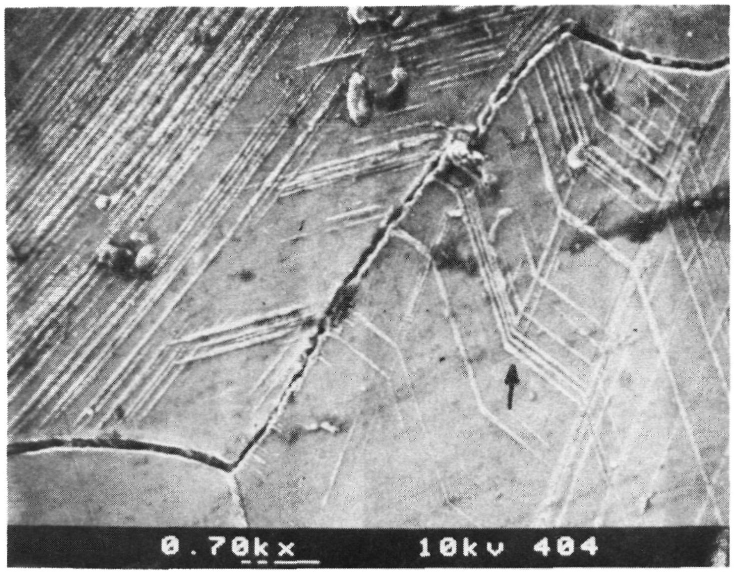


(b)

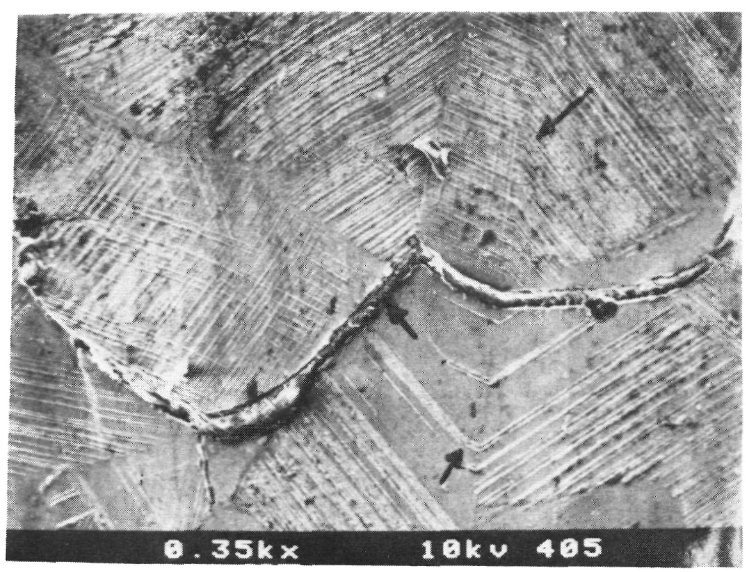
Fig. 8 a) Micrograph showing primary crack normal to the loading axis.

b) Mixed mode crack initiation and transgranular crack propagation. Note multiple slip systems operating, also deformation twining is observed.

SPEC. AXIS

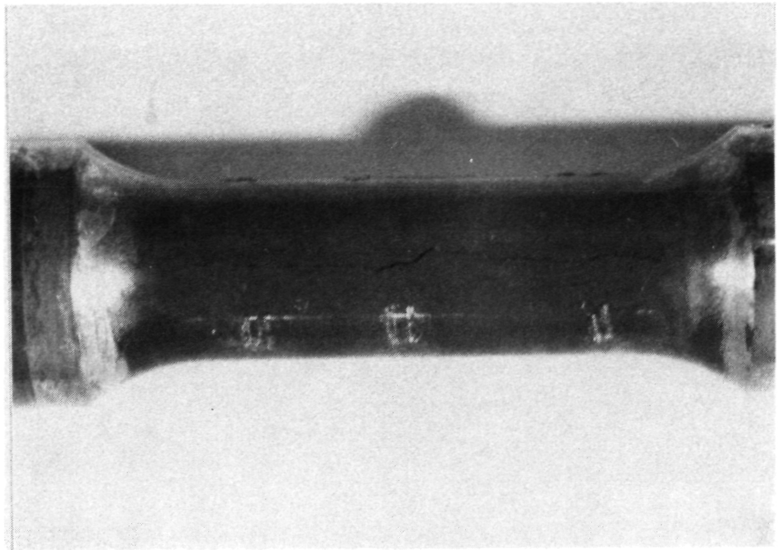


(a)

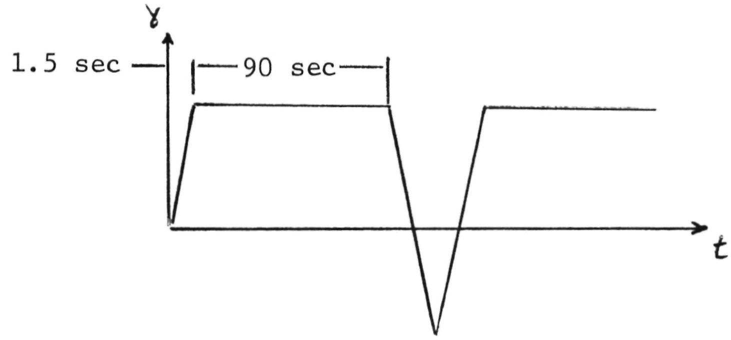


(b)

Fig. 9 a,b) Slip bands intersecting oxidized grain boundaries induced cracking, also multiple slip systems and deformation twining is observed.



(a)

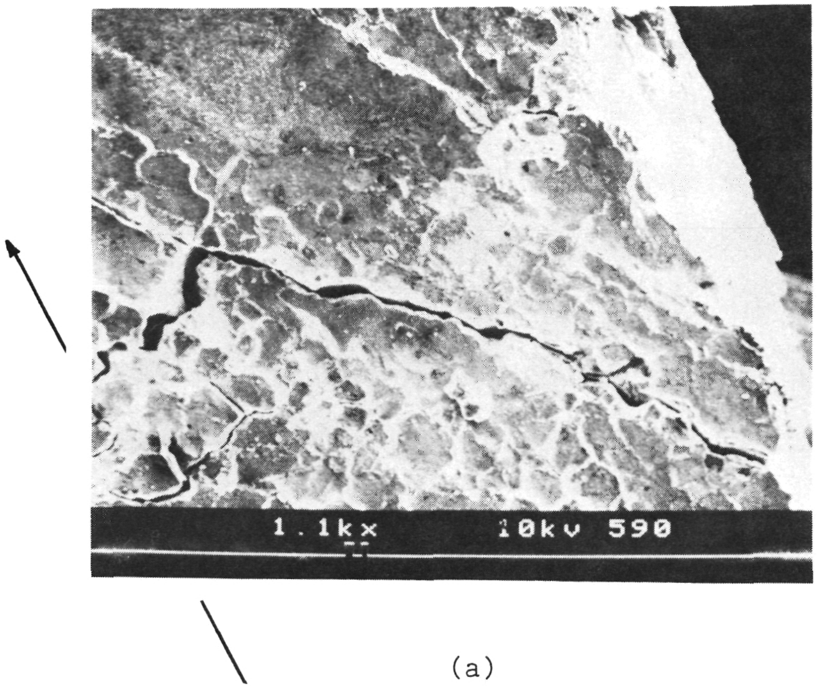


(b)

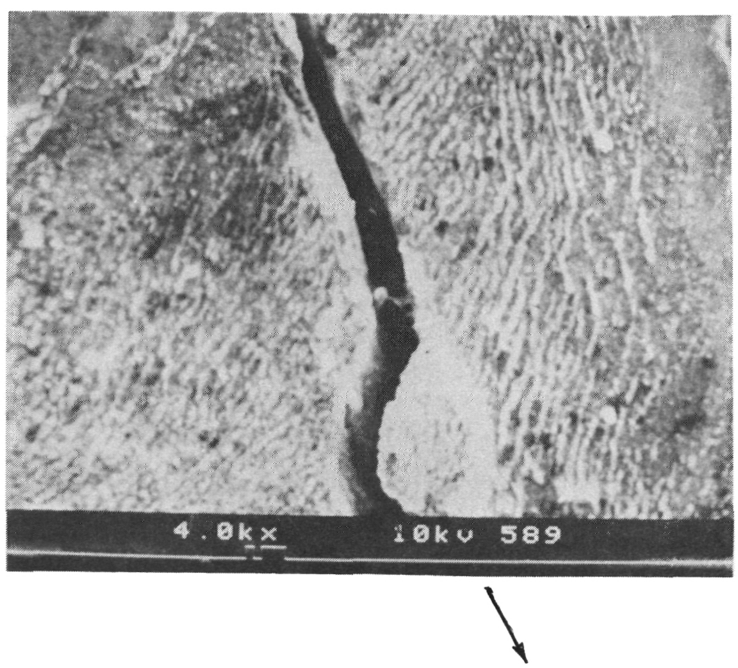
Fig. 10 a) Macrophoto of Waspaloy fine grain: Torsion with hold time. (Spec.BA13, $\Delta\gamma_T$=1.94%, $\Delta\gamma_{in}$=0.558% @ $N_f/2$, N_f=1653, T=1200°F, t=90 Sec.). Note primary crack is along the specimen axis

b) Applied wave form.

SPEC. AXIS



(a)



(b)

Fig. 11 a) Primary crack along the specimen axis, intergranular and transgranular cracking is observed, extensive oxiedation on the grain boundaries.

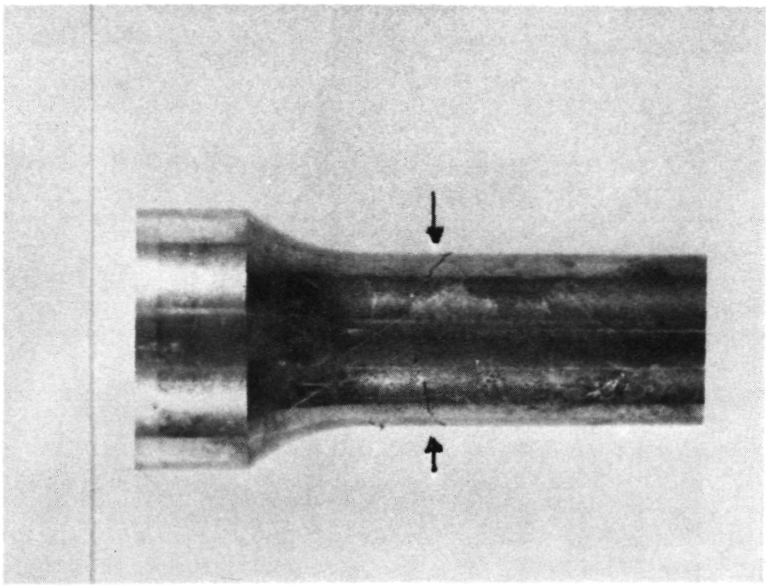
b) Note wavy and oxidized slip bands.

SPEC. AXIS

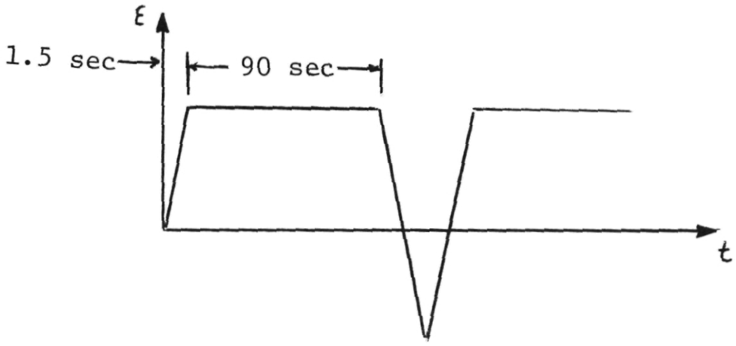
(a)

(b)

Fig. 12 a,b) Replicas of the gage section along the major crack showing extensive grain boundary oxidation. Note some large grains with straight slip are present.



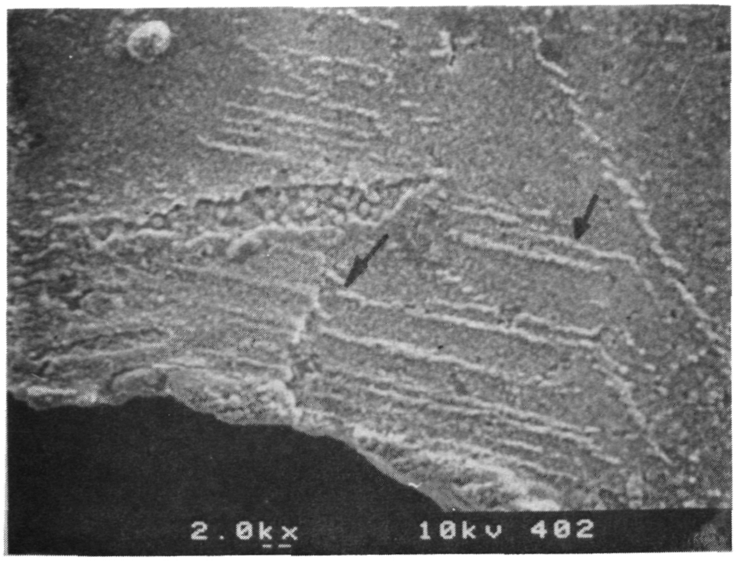
(a)



(b)

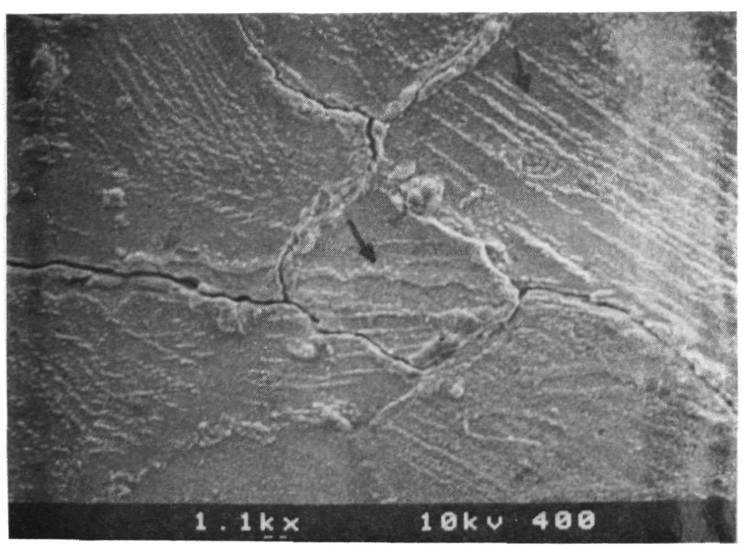
Fig. 13 a) Macrophoto of waspaloy fine grain: Axial with hold time. (Spec. BA30, $\Delta\varepsilon_T$=1.01%, $\Delta\varepsilon_{in}$=0.32% @ $N_f/2$, N_f=587, T=1200°F, t=90 Sec.) Note primary cracking normal to the loading axis.

b) Applied wave form.



SPEC. AXIS

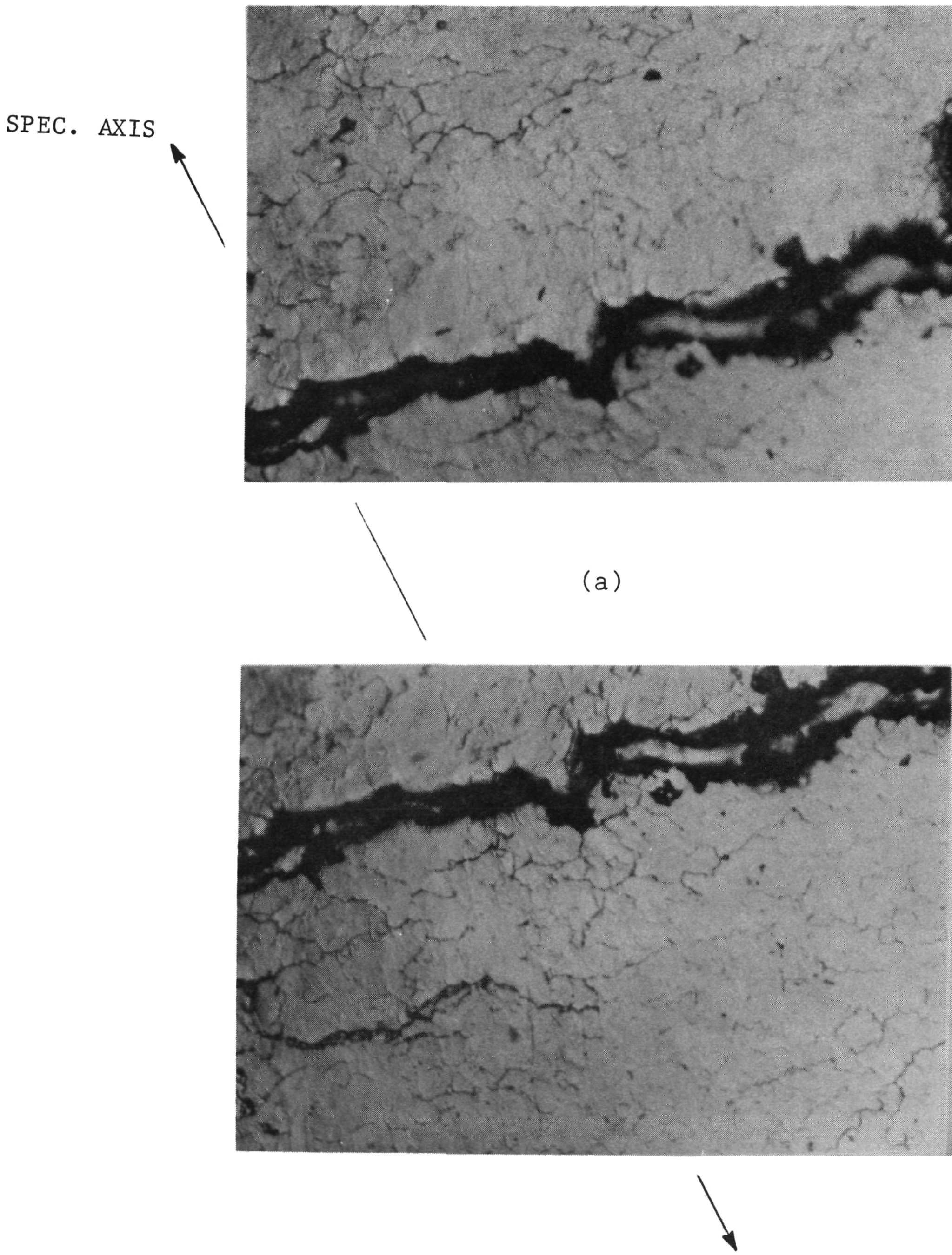
(a)



(b)

Fig. 14 a) Twin boundary cracking, oxidized slip bands are observed

b) Cracking along the grain boundaries, also note wavy slip bands



(a)

(b)

Fig. 15 a,b) Replicas of the gage surface at 40X, extensive grain boundary cracking above and below the primary crack are observed.

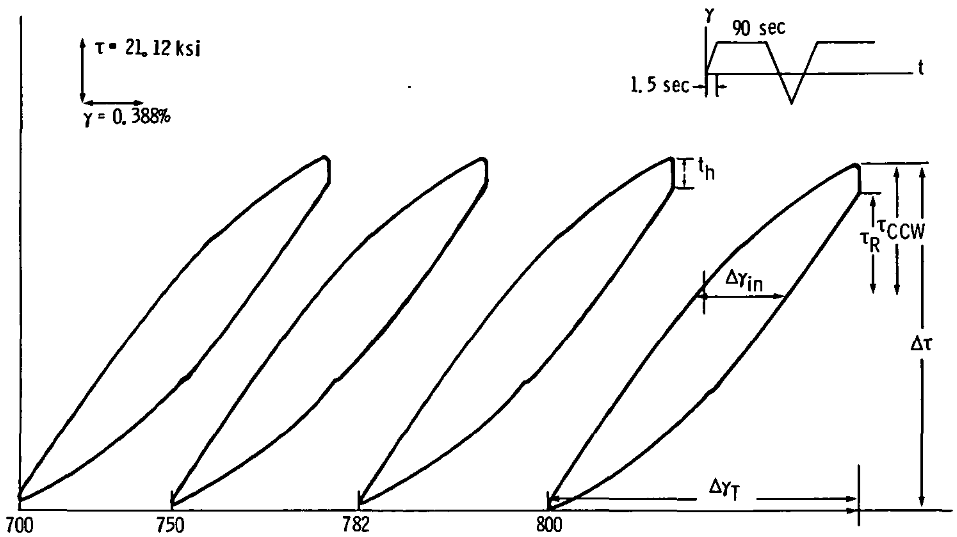


Fig. 16) Torsional hysteresis loops for small grain Waspaloy (Spec. BA13), tested at 1200 °F under 90 sec hold time. ($\Delta\gamma_T$ = 1.94%, $\Delta\gamma_{in}$ = 0.558% at $N_f/2$, N_f = 1653).

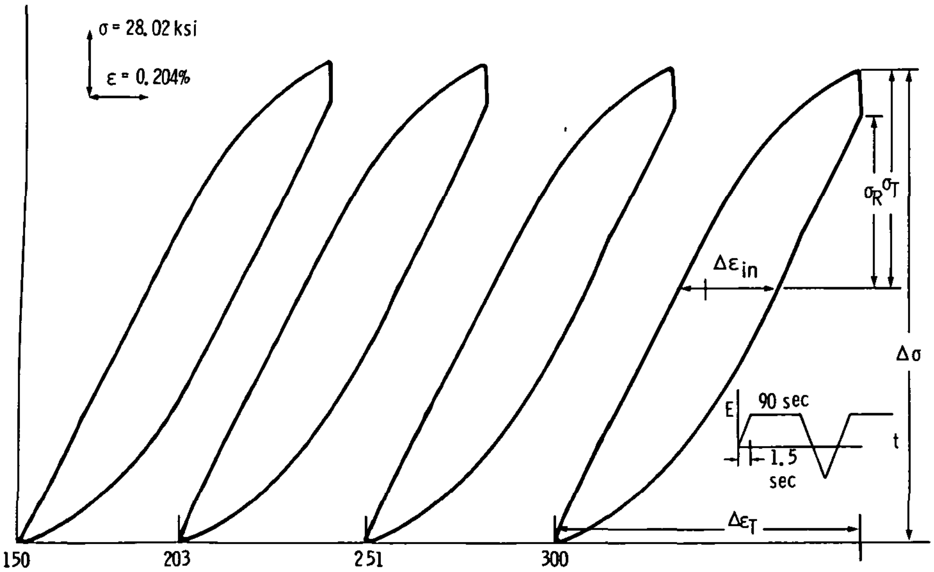


Fig. 17) Uniaxial hysteresis loops for small grain Waspaloy (Spec. BA30), tested at 1200 °F under 90 sec tension hold time. ($\Delta\varepsilon_T$ = 1.01%, $\Delta\varepsilon_{in}$ = 0.32% at N_f = 587).

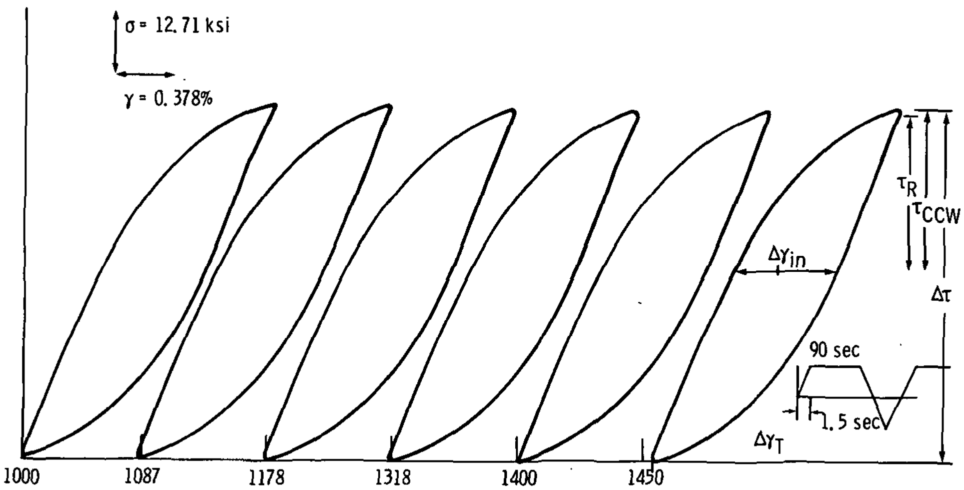


Fig. 18) Torsional hysteresis loops for large Waspaloy (Spec. BF25), tested at 1200 °F under 90 sec hold time. ($\Delta\gamma_T$ = 1.55%, $\Delta\gamma_{in}$ = 0.643 at $N_f/2$, N_f = 2691).

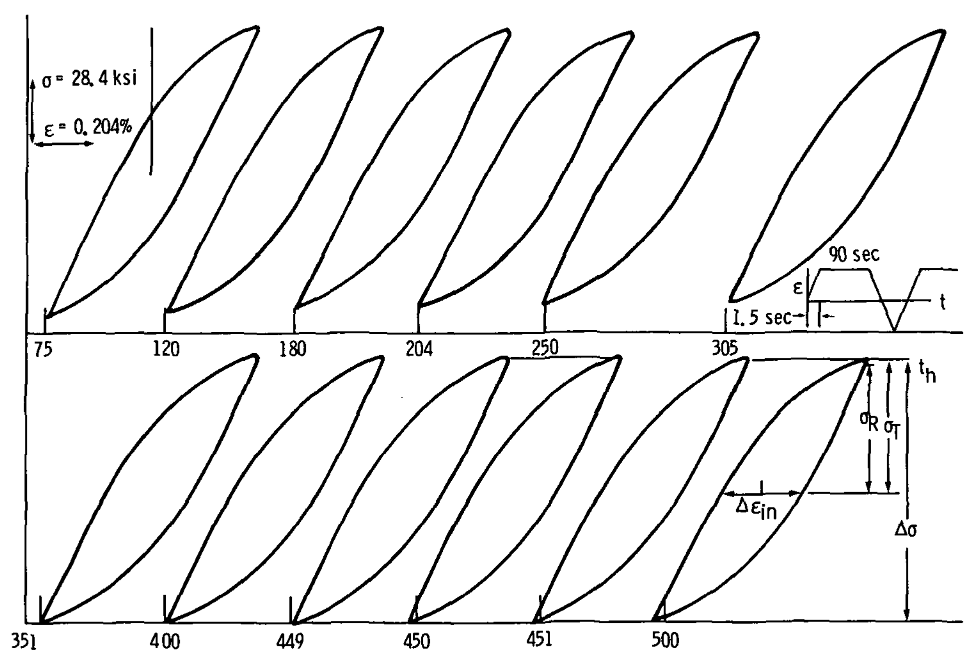


Fig. 19) Uniaxial hysteresis loops for large grain Waspaloy (Spec. BF8), tested at 1200 °F under 90 sec tension hold time. ($\Delta\varepsilon_T$ = 0.70%, $\Delta\varepsilon_{in}$ = 0.29% at $N_f/2$, N_f = 987).

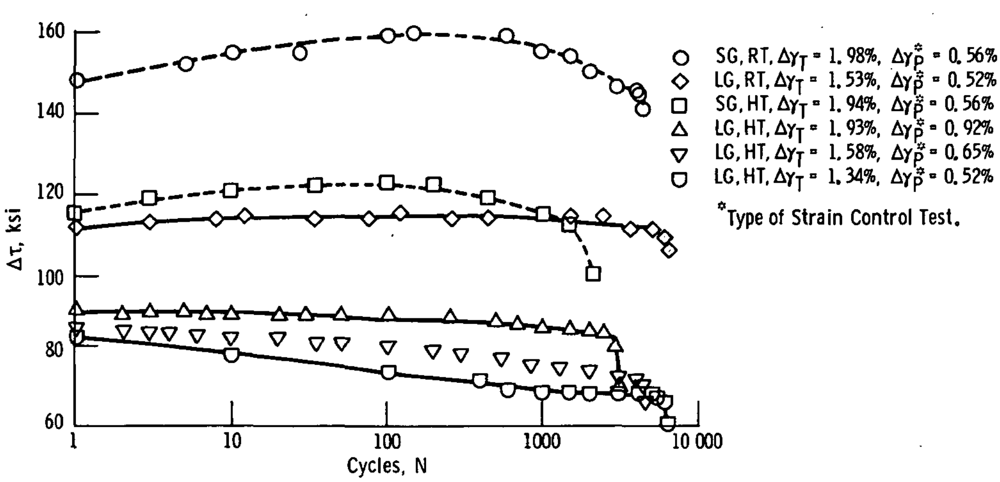


Fig. 20) Shear stress range variation with cycle for small grain (SG) and large grain (LG) Waspaloy, tested under continuous cycling (10 cpm) at room (RT) and 1200 °F (HT) temperatures.

1. Report No. NASA CR-175052 USAAVSCOM TR-86-C-14	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Axial and Torsional Fatigue Behavior of Waspaloy		5. Report Date April 1986
		6. Performing Organization Code
7. Author(s) S. Zamrik, M. Mirdamadi, and F. Zahiri		8. Performing Organization Report No. None
		10. Work Unit No.
9. Performing Organization Name and Address The Pennsylvania State University Engineering Science and Mechanics Dept. University Park, Pennsylvania 16802		11. Contract or Grant No. NAG 3-264
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address U.S. Army Aviation Research and Technology Activity - AVSCOM, Propulsion Directorate, Lewis Research Center, Cleveland, Ohio 44135 and NASA Lewis Research Center, Cleveland, Ohio 44135		14. Sponsoring Agency Code 505-63-11

15. Supplementary Notes

Final report. Project Manager, Robert C. Bill, Propulsion Directorate, U.S. Army Aviation Research and Technology Activity - AVSCOM, Cleveland, Ohio 44135.

16. Abstract

The cyclic flow response and crack growth behavior of Waspaloy at room temperature and 650 °C under tensile loading and torsional loading was studied, for two conditions of Waspaloy: fine grain, large γ' size; coarse grain, small γ' size. The fine grain material showed 5 to 10 percent hardening after about 10 percent of life, with sequent softening to failure at both temperature levels. The coarse grain material showed either stable response or monotonic softening to failure. Early crack initiation was observed on planes of maximum shear, with eventual branching to principal planes under torsional loading; cracks were always normal to load axis under tensile loading. Also, crack paths were intergranular at 650 °C, mostly transgranular at room temperature.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fatigue; Tension; Torsion; High temperature; Superalloy; Waspaloy	Unclassified - unlimited STAR Category 26

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	22	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

Official Business
Penalty for Private Use $300

SECOND CLASS MAIL

ADDRESS CORRECTION REQUESTED

U.S. MAIL

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

NASA