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ANALYSIS OF SINGLE CRYSTAL NiAl
TURBINE BLADES (NASA. Lewis
Research Center) 11 p

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RELIABILITY ANALYSIS OF SINGLE CRYSTAL NiAl TURBINE BLADES

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Introduction

As part of a co-operative agreement with General Electric Aircraft Engines (GEAE), NASA LeRC is modifying and validating the Ceramic Analysis and Reliability Evaluation of Structures (CARES ref. 1) algorithm for use in design of components made of high strength NiAl based intermetallic materials.

NiAl single crystal alloys are being actively investigated by GEAE as a replacement for Ni-based single crystal superalloys for use in high pressure turbine blades and vanes. The driving force for this research lies in the numerous property advantages offered by NiAl alloys (ref. 2) over their superalloy counterparts. These include a reduction of density by as much as a third without significantly sacrificing strength, higher melting point, greater thermal conductivity, better oxidation resistance, and a better response to thermal barrier coatings. The current drawback to high strength NiAl single crystals is their limited ductility. Consequently, significant efforts including the work agreement with GEAE are underway to develop testing and design methodologies for these materials.

The approach to validation and component analysis involves the following steps (Fig. 2): determination of the statistical nature and source of fracture in a high strength, NiAl single crystal turbine blade material; measurement of the failure strength envelope of the material; coding of statistically based reliability models; verification of the code and model; and modeling of turbine blades and vanes for rig testing.

Material Testing and Specimen Design

Brittle materials frequently fail from a single, strength limiting origin due to low toughness. The strength of such a system is thus governed by the weakest-link within the system and is therefore dependent on the surface area and volume stressed during testing. Weibull statistics (ref. 5) are commonly used for reliability analysis of components fabricated from such materials. The calculated failure probability is dependent on the stress state and the material properties of the component.

Several isotropic theories applicable to ceramics and glasses have been incorporated into the public domain CARES (ref. 1) code developed at NASA Lewis. This post-processor code, when combined with a finite element stress analysis, calculates fast fracture probability of a brittle, monolithic structural component. As part of the cooperative agreement with GEAE the code will be modified to model anisotropic materials, such as single crystal NiAl.

The material being considered has limited ductility, is highly anisotropic (Young's modulus varies 95 to 271 GPa; 13.78 E3 ksi to 39.305 E3 ksi) and made in relatively small billets (25 x 50 x 100 mm; 0.98 x 1.96 x 3.94 in.) that will be used individually to produce a vane or blade. Therefore, the statistical nature and

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source of fracture is being studied via flexural testing of beam specimens (ref. 3), with statistical analysis of the data and fractography performed on all of the post-tested samples (ref. 4). Flexural testing allows many samples to be removed from a particular region of a given billet, thereby allowing determination of billet-to-billet and within billet consistency. These factors will cause a variation in component reliability. Furthermore, in contrast to tensile testing, flexural testing allows the location of failure to be readily identified because the asymmetry of flexural loading results in a specific fracture pattern.

Two basic types of flaws are typically encountered in brittle materials such as ceramics or glasses: surface defects and volumetric defects. Volumetric defects include large grains, pores, agglomerates and inclusions, while surface defects include exposed volume defects (e.g. a pore machined open) and machining or handling damage that occurs during specimen/component fabrication (ref. 4).

Flexural strength results for the single crystal NiAl indicate the material to exhibit a wide dispersion in strength (Fig. 3) that can be characterized via normal or Weibull statistics. Failure origins were identified in 27 of 29 specimens tested. In all cases failure originated from regions of interdendritic precipitation (Fig. 4). These interdendritic regions always contained a Ni-Al-Hf rich phase (Fig. 5) that was confirmed by x-ray analysis to be the Heusler phase Ni_2AlHf. Roughly half of the initiation sites also contained HfC dendrites within the interdendritic Heusler phase (Fig 6). The HfC phase was identified by Auger electron spectroscopy and confirmed by the shape of the carbon peak (Fig. 7).

Other strength tests planned for verification work include flexure (3 and 4-point), pure tension, pure compression, torsion and biaxial flexure. To date, uniaxial and biaxial flexural tests (Fig. 3) have been conducted, and a torsion specimen is being designed and verified relative to handbook solutions. Verification of a failure theory can be accomplished via measurement of points on the failure envelope and comparison to predictions by the model and code (Fig. 8). Each point on the failure envelope represents a stress state and thus can be measured experimentally for a given material via strength testing with various geometries. As the material exhibits elastic anisotropy and variation in fracture toughness with orientation (ref. 7), several orientations will be considered in strength testing.

For the torsion specimen design, in an effort to conserve time, materials and machining costs, finite element analysis was used to characterize the stress response of several specimens. A baseline model and several variations were analyzed using the ANSYS 5.0 finite element package. The intent was to optimize the stress response of the specimen such that highest stresses would occur in the gage section of the specimen, thus concentrating failure within this section. Upon completion of the stress analysis, a CARES analysis was conducted for each specimen as well.

Each model consisted of three parts: the specimen, a three jaw chuck assembly used to grip the specimen, and a sleeve of surface elements around the volume of the specimen (see Fig. 9). Note that only half of the length of the specimen was modeled to take advantage of symmetry. A desired maximum principal stress of 800 MPa (116.0 ksi) was specified for each specimen. To obtain this stress level, a tangential force in the circumferential direction was applied at third points to the extremities of the chuck assembly.

A total of nine specimen geometries were analyzed. The use of parametric design language within ANSYS facilitated easy manipulation of design variables and model creation. The transition length between the gage section and the grip section of the specimen served as one design parameter. The gage diameter was the other. The different values for these parameters appear in Fig. 10. The intent was to eliminate stress risers in the transition section of the specimen and keep the maximum stress within the gage section. A constant, low stress field was also desirable in the grip section of the specimen. The baseline design satisfied both of these requirements. A plot of the first principal stress for this model is shown in Fig. 11. As the gage section of the specimen became larger, higher stresses began to migrate into the transition section and beyond into the grip section. Also, as the transition length between the grip and gage sections was changed, higher stresses began to migrate into the transition section. Of the nine designs, no model behaved better than the baseline design.

The subsequent reliability analyses reinforced these results. Developing a specimen with high probability of failure in the gage section and low or no probability of failure in the transition and grip sections was the objective. Since it is anticipated that this material will exhibit the so called "size effect" (i.e., decreasing component strength with increasing component size), the overall stressed area of the component would likely affect the reliability results. This factor was monitored as the results of the different models were compared. Again, the various iterations in the design provided no reason to switch from the baseline specimen design.

Component Analysis

As a starting point for the component feasibility study, a two dimensional finite element model of a double tang blade post and disk assembly was obtained from General Electric (see Fig. 12). This was used with the NiAl failure data (Fig. 3) to perform the reliability analysis. Fig. 13 shows the approach used for this type of analysis. Using this approach, the design engineer can concentrate on areas of the component which possess low reliability and modify them accordingly, thus leading to the optimization of the component.

Only the blade dove tail section was considered in the reliability analysis. Two separate analyses were conducted. The first used the entire set of 29 failure data points to calculate the Weibull parameters. The second involved the assumption that through improved processing techniques, the lowest five failure points would be eliminated, hence the Weibull parameters were calculated from the 24 highest failure strength values. The results of the reliability analysis and the respective Weibull parameters appear in Fig. 14. This analysis clearly shows the effect that reduced scatter has on a reliability of a component fabricated from a brittle material system.

This effort was successful in demonstrating the feasibility of such design procedures; however, to fully characterize a component fabricated from this type of material system, a failure criterion has to be developed that captures the anisotropic behavior of the material. This is a subject for future work and is identified as a milestone within the work agreement. Other areas of future work include a more complete characterization of the material's behavior along various crystallographic orientations. Billet to billet strength variation as well as strength variation within each billet will also be monitored.

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OBJECTIVE

- Modify and validate the CARES reliability code for use in design of components made from low ductility NiAl based intermetallics.

- This effort is part of a co–operative work agreement between General Electric Aircraft Engines and NASA LeRC.

Fig. 1 CD-94-68043

APPROACH

- Determine the statistical nature and source of fracture in high–strength NiAl single crystal material
- Measure the fracture strength envelope of the material (may involve characterizations in different material directions)
- Develop and code the appropriate failure model to capture both the statistical nature of failure and the anisotropic behavior of the material
- Verify the model and reliability code
- Model turbine vanes and blades for rig testing

Fig. 2 CD-94-68044

WEIBULL PLOT OF FAILURE DATA

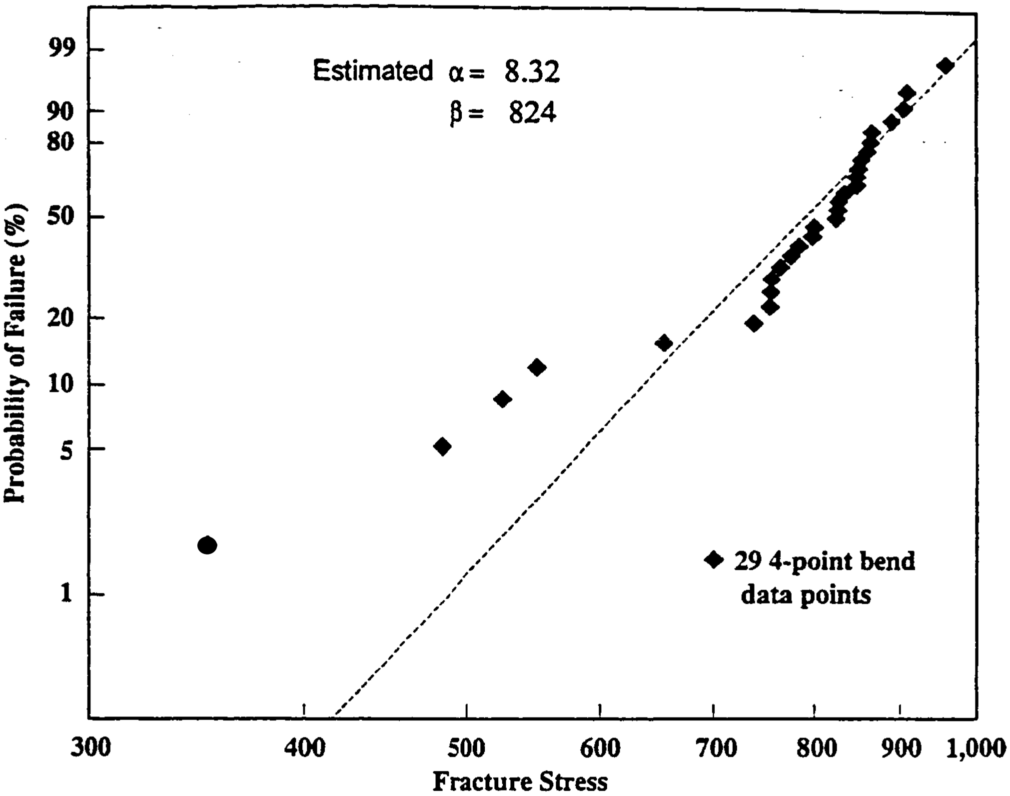


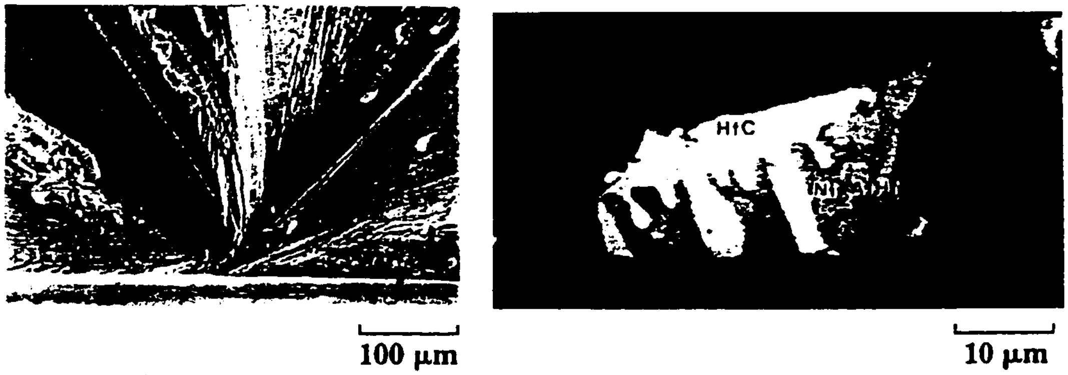
Fig. 3

CD-94-68045

NiAl TEST SPECIMEN FRACTOGRAPHY

— Fractography (SEM/EDS) was performed on 27 of 29 specimens (Origins for 2 were not recovered)

— All had fracture origins at Ni_2AlHf or HfC particles or a combined interdendritic particle



SEM image of failure origin

High mag. image of failure origin

Fig. 4

CD-94-68046

AUGER ANALYSIS SHOWING HEUSLER PHASE

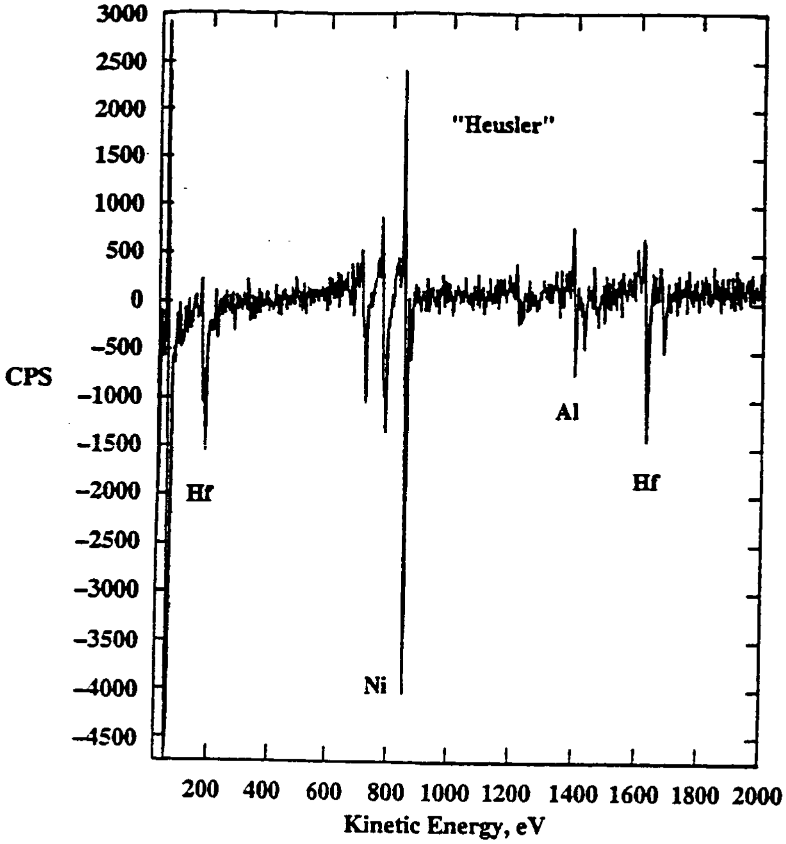


Fig. 5

CD-94-68047

AUGER ANALYSIS SHOWING HfC PHASE

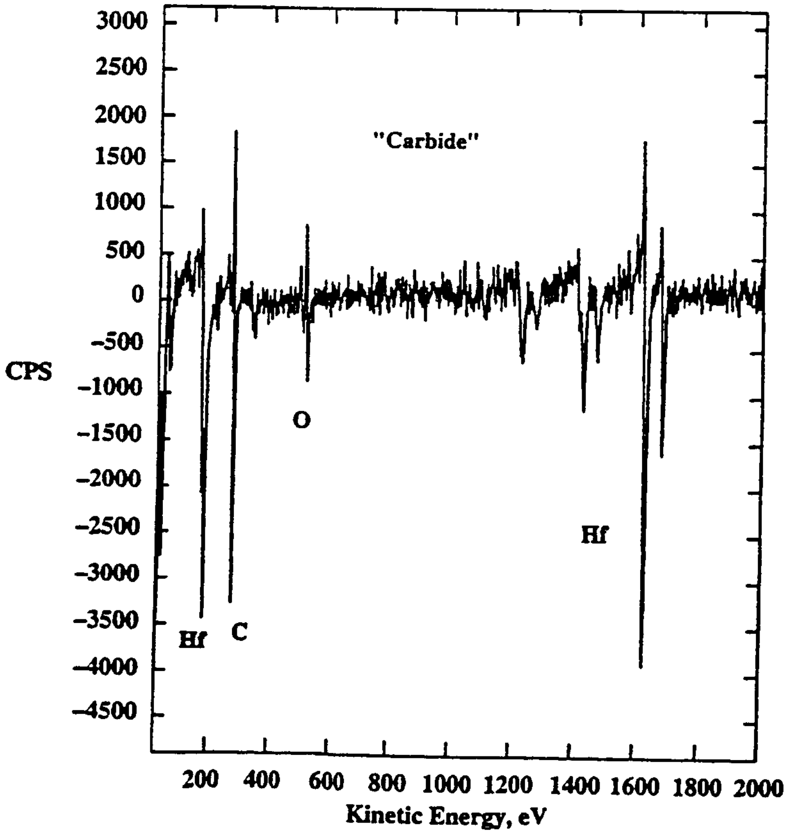


Fig. 6

CD-94-68048

DETAILED AUGER ANALYSIS OF CARBON REGION

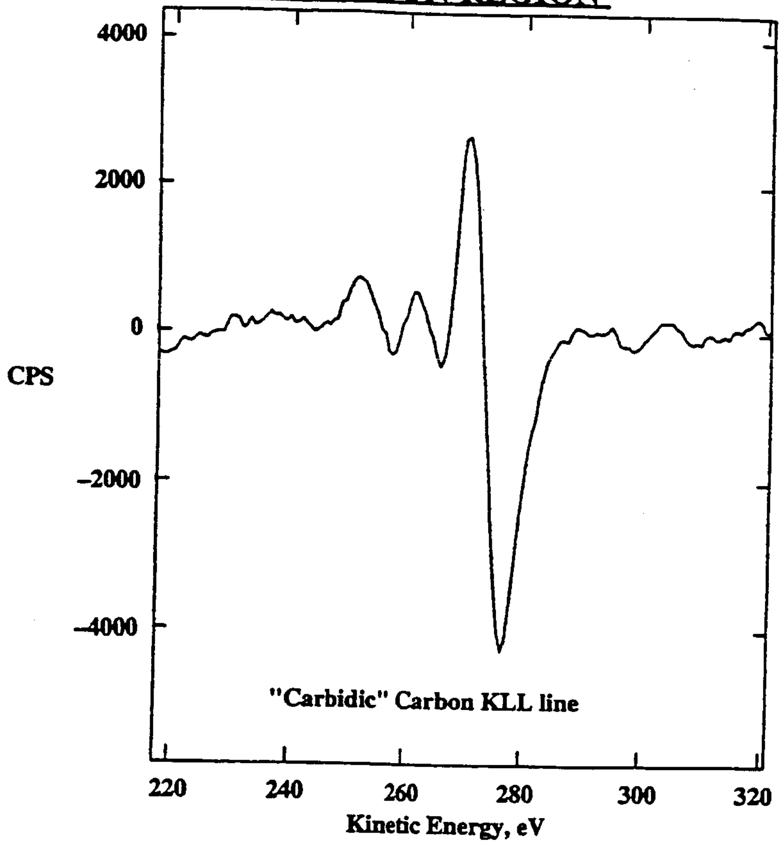


Fig. 7

CD-94-68049

COMPARISON OF FAILURE DATA WITH THEORY

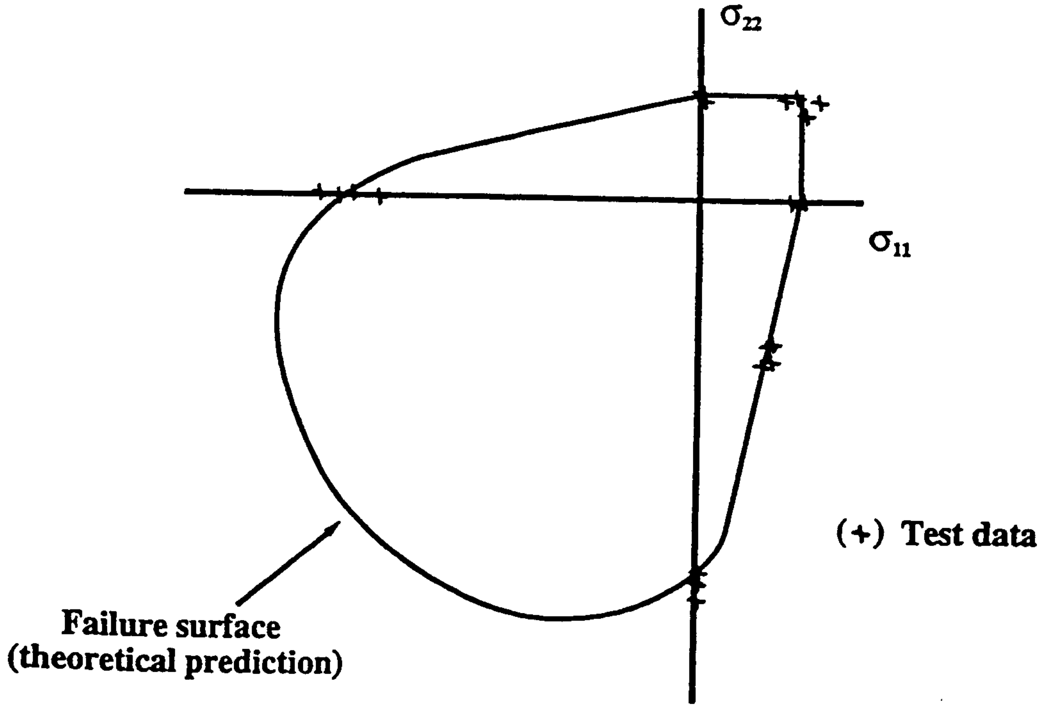


Fig. 8

CD-94-68050

TEST SPECIMEN ANALYSIS

Finite element model of specimen and chucks

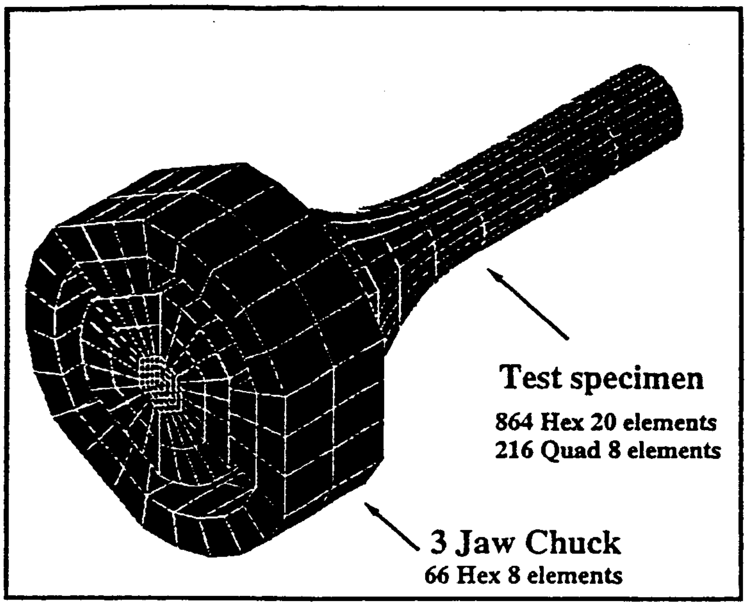
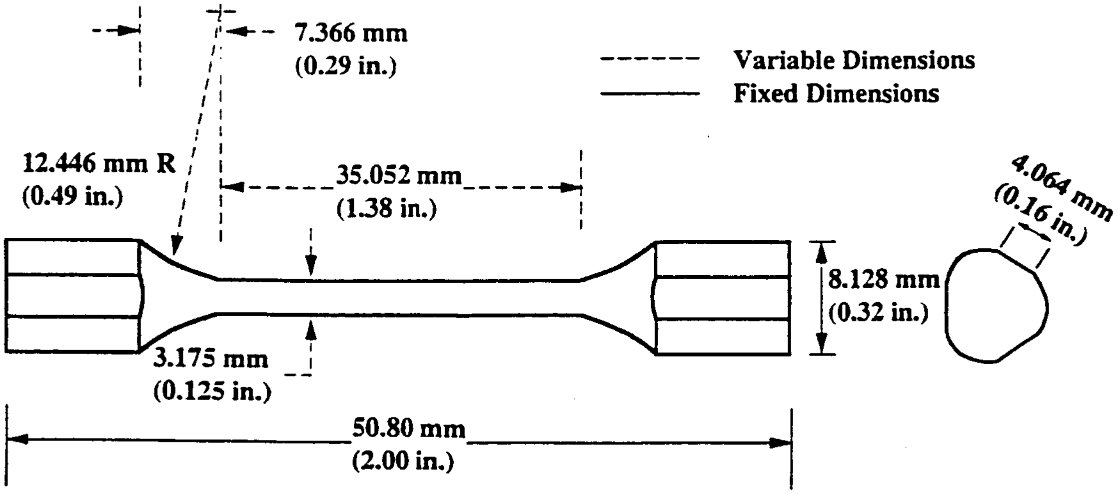


Fig. 9

CD-94-68051

TEST SPECIMEN
(BASE DESIGN)



Gage Diameters: 3.175 mm, 3.810 mm, 4.445 mm
(0.125 in.) (0.150 in.) (0.175 in.)
Transition lengths: 7.366 mm, 5.004 mm, 3.505 mm
(0.29 in.) (0.197 in.) (0.138 in.)

Fig. 10

CD-94-68052

PRINCIPAL STRESS PLOT OF BASELINE TORSION SPECIMEN

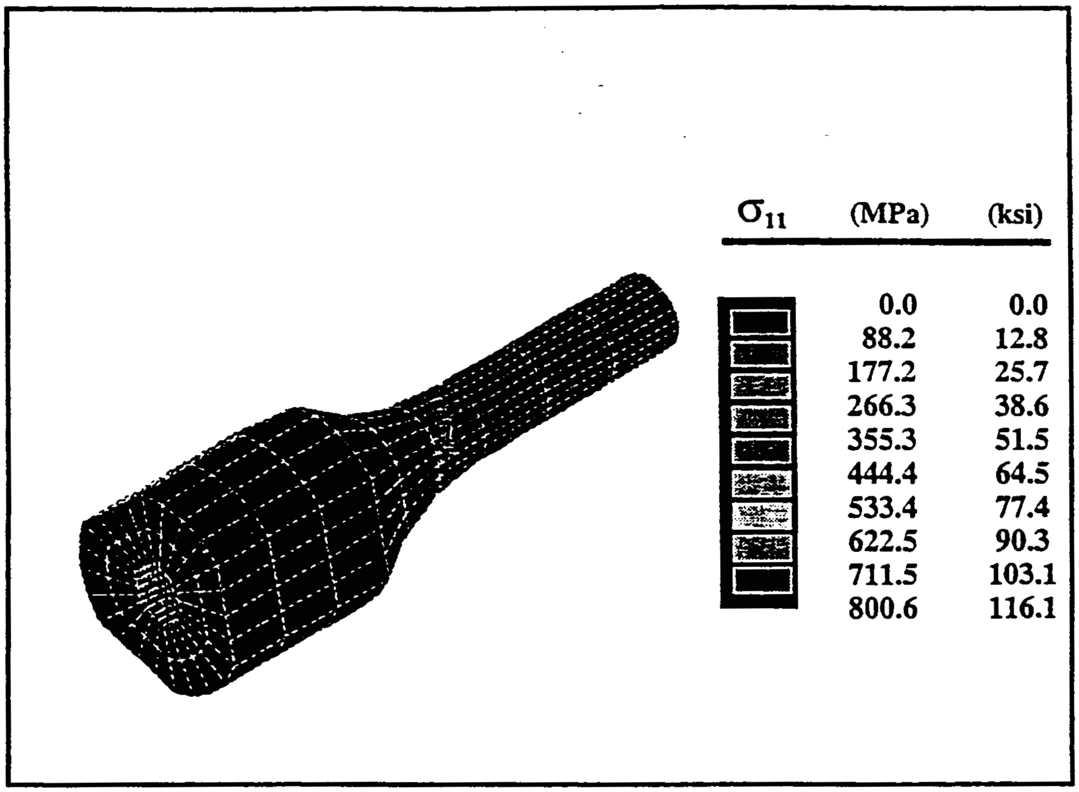
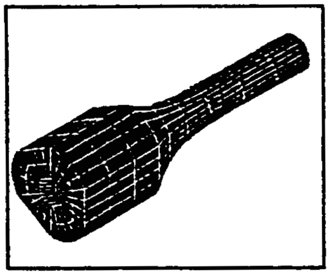


Fig. 11

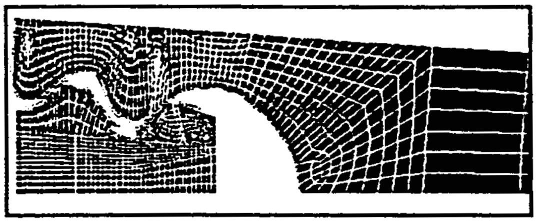
CD-94-68053

PROBABILISTIC COMPONENT DESIGN PROCEDURE

- Approach:



Test Specimen



Complex Geometries

—— Material failure characterization

—— Fractographic examination of ruptured specimens

—— Component finite-element analysis

—— Component reliability evaluation

—— Design optimization

Fig. 12

CD-94-68054

BLADE AND DISK ANALYSIS

Finite element model of blade post and disk assembly

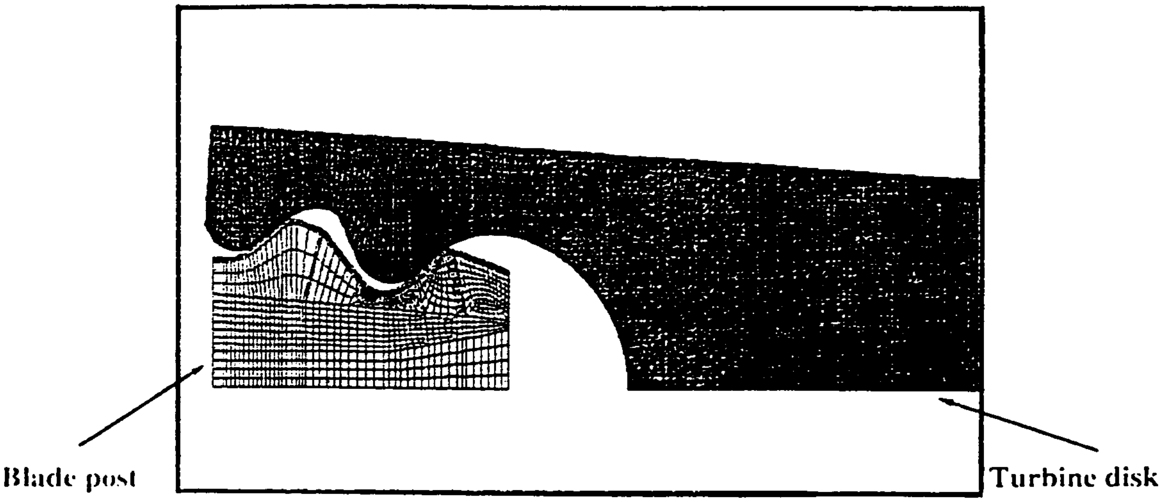


Fig. 13 CD-94-68055

SUMMARY OF CARES ANALYSIS OF BLADE

Two reliability analyses were conducted on blade design

– Two sets of Weibull parameters were used

	29 Data points	24 Data points
Alpha	8.32	15.30
Beta $(\text{ksi})^{3/\alpha}$	51,021	74,092
Reliability	99.46%	99.99%

Fig. 14 CD-94-68056

CONCLUSIONS

- Failure origins can be identified in low ductility NiAl's with appropriate testing
- Torsion specimen geometry was verified through FEM and CARES analyses
- Methods in place for component reliability analyses
- Improved processing techniques can be used to improve component reliability

Fig. 15 CD-94-68057

FUTURE WORK

- Test material for billet to billet strength variation
- Test material for strength variation within a billet
- Test for statistical variation along different material directions
- Develop appropriate failure model for this material

Fig. 16 CD-94-68058