RESIDUAL STRESSES: TOOLS FOR OPTIMIZING COMPONENT PERFORMANCE

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Residual Stresses: Tools For Optimizing Component Performance

Outline:
• Residual Stress Effect on Fatigue
• Processes That Produce Residual Stress
• Surface Treatments
• Review of LPB Process
• Example – LPB of Ti-6Al-4V Neck Segment
• LPB Process Control
• Conclusions
Residual Stress Definition

Stresses That Exist In An Elastic Solid Body With All External Loading Removed
Residual Stress Effect on Fatigue

- Manufacturing Processes Create RS
- RS Can Be As Large As Yield Level
- Surface Is Weaker in Fatigue Than Subsurface
- Compressive RS Beneficial in Fatigue
- Tensile RS Detrimental in Fatigue
Residual Stress Effect on Fatigue

Alternating Applied Stress

\[ R = \frac{S_{\text{min}}}{S_{\text{max}}} = -1 \]

S-N Curve

\[ R = -1 \]
Residual Stress Effect on Fatigue

\[ S_{mean} = \frac{(S_{min} + S_{max})}{2} \]

Fatigue Strength Reduced

Fatigue Strength Increased

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Residual Stress Effect on Fatigue

HCF strength increases with subsurface compression.

Endurance limit increases linearly with compression: 4X

Shot Peened 1070 Spring Steel

Surface compressive layer retards crack initiation and growth.


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**FATIGUE DESIGN DIAGRAM**

For Ti-6Al-4V STA, the diagram illustrates fatigue design considerations. The stress levels are categorized into:

- **Safe**
- **Restore**
- **Enhance**
- **No Mode I Cracking Possible**

The diagram uses the following symbols:

- $S_{alt}$ ksi: alternating stress
- $S_{mean}$ ksi: mean stress
- $N_t = 10^7$ cycles

$RS_{max}$ and $RS_{min}$ are the upper and lower bounds, respectively.

$RS_{optimum}$ can be determined by taking into account part distortion and compensatory tension.
How Are Residual Stresses Formed

• RS Result From Strain Gradients (Differences in Strain From One Location to the Next)

• Most Manufacturing Processes Produce RS
  – Machining – Milling, Turning, Grinding, EDM
  – Heat Treatment – Carburizing, Nitriding, Induction Hardening
  – Joining – Welding, Brazing
  – Surface Treatment – Shot Peening, Burnishing, Laser Shock Processing (LSP), Low Plasticity Burnishing (LPB)
Residual Stress Measurement

**LINEAR ELASTIC METHODS**

Mechanical
1) Various dissection methods
2) Ring core
3) Center-hole drill (ASTM E837)

Diffraction
1) X-ray
2) Neutron

**NON-LINEAR ELASTIC METHODS**

Magnetic
1) Barkhausen noise
2) Eddy Current

Ultrasonic
Machining Residual Stresses

**TURNING**

![Graph showing residual stresses for Ti-6Al-4V ROUND BAR](image)

**MILLING**

![Graph showing residual stresses for Ti-6Al-4V TEST COUPON](image)

**EDM**

![Graph showing residual stresses for Ti-6Al-4V TEST COUPON](image)
Welding Residual Stresses

Ti-6Al-4V Friction Stir Weld
Longitudinal Direction
Surface Treatments

- Shot Peening
- Heat Treatment
- Hole Expansion
- LPB
- Burnishing
- Laser Peening
Shot Peening

Impact of shot at high speed creates surface deformation in the form of a dimple.

Deformed in Tension

**SHOT PEENING**

**RESIDUAL STRESS DISTRIBUTIONS**

- Residual Stress (ksi)
- Residual Stress (MPa)

*Ti 6Al-4V*
Heat Treatment

- Carburizing
- Nitriding
- Induction Hardening
- Heat & Quench

Hoop RS in Turbine Disk Following Heat Treat and Quench

http://materials.open.ac.uk/staff/staff_mr.htm
Hole Expansion

Circumferential Residual Stress

7075 ALUMINUM TEST COUPON
Inside Diameter Mid-Length of Expanded Hole
Laser Peening

Longitudinal Residual Stress

Ti-6Al-4V TEST SAMPLE
Longitudinal Residual Stress

www.substech.com
How to Choose a Surface Treatment

- Component Geometry & Operating Environment
  - Part Cross Section
  - Baseline Residual Stress Condition
  - Accessibility of Critical Region/s
  - Operating Temperature
  - Magnitude of Applied Stresses

- Damage Mechanism
  - Corrosion Pits
  - FOD
  - Fretting Damage

- Distortion Limits

- Surface Finish

- Production Requirement
  - Cycle Time & Part Volume
  - Logistics
  - Quality Control
  - Costs (Capital Equipment, O&M)
PRODUCTION LPB APPLICATION
M-Series Modular Hip System

- Neck segment
- Metaphyseal
- Affected region
- Femur
- Femoral stem
LPB Technology

- High-hardness ball is rolled, under pressure, over surface
- Single pass provides deep compression
- Patented hydrostatic bearing with constant volume flow
- Low cold work < 3.5-5% provides stable compression

![CONSTANT VOLUME FLOW BEARING (PATENTED)]

![RESIDUAL STRESS DISTRIBUTION]

![PERCENT COLD WORK DISTRIBUTION]

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Features of Low Plasticity Burnishing (LPB)

- Low magnitude controlled cold working
- Thermal and Mechanical (Overload) stability
- Easily performed on CNC tools in a machine shop
- Applicable to arbitrary shapes and directions
- Rapid processing (>2000 sfm in turning)
- Deep compressive layer (~1mm, up to 12 mm)
- High magnitude compression (~YS)
- Established QA of a mechanical manufacturing system
- Improves HCF and SCC by mitigating damage without changing material or design
LPB Tool Technology

Single-Point Tool for thick pieces or one-sided application

Caliper Tool for thin pieces, providing through thickness compression

Through-thickness compression in compressor blade LE

Disk slot tools and inside calipers for ID bores built in 2006
LPB CNC Production Tooling

- Machining-like operation using typical CNC machine tools or robots for precise, reproducible processing
- Highly automated...minimal operator intervention
- Low capitalization costs...use existing CNC machines
- Shop floor and logistically compatible...no specialized or remote facilities required
Baseline Fractography

Fatigue Initiations

Fretting on O.D. of Neck

Multiple Cracks Along Length of Neck

12 o’clock

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Fretting Fatigue Overview

• Fretting occurs when two mating parts, are pressed together, and are subjected to a transverse cyclic loading typically less than 0.004 in. (0.1 mm). (1)

• Fretting can cause metal-to-metal adhesion or “microwelds “.

• Weld edges are susceptible to high cyclic shear stress from which microcracks can propagate.

• Microcracks are typically on the order of a few thousandths of an inch.

• In the absence of a sufficient depth of compressive residual stress the microcracks can grow into macrocracks leading to a significant reduction in component fatigue strength and life.

Finite Element Mesh

Force Applied to Femoral Head

Neck Segment

Constrained Neck Taper
Finite Element Determination of Applied Stress

Maximum Tension
Near 12 o’clock

Maximum Compression
Near 6 o’clock
Finite Element Determination of Applied Stress

Load Case: 1 of 1
Maximum Value: 64952.3 lbf/(in^2)
Minimum Value: -165627 lbf/(in^2)
Low Plasticity Burnishing of Neck Stem

LPB Tool

Neck Stem
X-Ray Diffraction Residual Stress Results

- 5X Surface Compression
- 0.03 in. Depth of Compression
Finite Element Prediction of Residual Stresses

Full Model

Cross-Section

360 deg. of Compression In Tapered Region

O.D. Compression

I.D. Tension < +15 ksi
Applied + Residual Stress

Distance From Tip of Tapered Neck (mm)

Nominal Baseline
Fatigue Strength
Radius Start

Stress (ksi)

-150
-125
-100
-75
-50
-25
0
25
50
75
100
125

Distance From Tip of Tapered Neck (in.)

Stress (MPa)

-1000
-800
-600
-400
-200
0
200
400
600
800

Applied Stress 1050 lbs
Applied Stress 1800 lbs
Applied 1050 lbs + Residual Stress (LPB)
Applied 1800 lbs + Residual Stress (LPB)
High Cycle Fatigue Test Set-Up

- Fatigue Testing Per ISO 7206-4,-8
- Bending + Torsion
- $R=0.1$
- Frequency = 15Hz
High Cycle Fatigue Results

• ~33% Increase in Fatigue Strength
• ~50X Increase in Life
• LPB Eliminated Fretting Failures In Tapered Region
• Metaphyseal Failures
Fatigue Life Improvement @ 1400 lbs

- LPB Treated
- Baseline

50X Life Improvement
Metaphyseal Fatigue Failures

Crack in Metaphyseal
Dedicated CNC Lathe Based LPB System for Processing Hip Neck Stems

CNC Control

LPB Control

LPB Hydraulics

LPB Tool Mounted in Cat 40 Tool Holder
Production Quality Assurance

• LPB process at extremes and test
• Real time monitoring of pressure
• Software written to verify pressures
• LPB process cycle time ~ 1 min.
FDA FAILURE HISTORY - EXACTECH MODULAR HIP SYSTEM

Number of Failures vs Year

2004  2005  2006  2007  2008

failures from hips installed before LPB processing

LPB Treatment Started Here

2009 - 2012
No Failures (After LPB Treatment)
Summary

• Manufacturing Processes Produce RS (- and +)
• RS Can Dramatically Effect Fatigue Properties
• Surface Treatments Can Be Used To Introduce Compressive RS Without Costly Changes in Alloy or Geometry
• Surface Treatment Depends On Many Factors (Part Geometry, Damage Mechanism, Production Requirements)
• LPB Increased Fatigue Strength by ~33% and Life by ~50X.
• Compressive RS Completely Eliminated Fatigue Failures From Fretting.
QUESTIONS?