SHOT PEENING APPLICATIONS AND FUTURE RESEARCH IN THE AEROSPACE INDUSTRY

NIHAD BEN SALAH

SAFRAN RESEARCH CENTRE (SAFRAN TECH), PARIS-SACLAY, FRANCE
“It’s not because an idea is crazy that it’s necessary wrong” (Mission to Mars)

My background

- 14 years academic

- 18 years aircraft industry: landing gears, engines, … in Canada and France

- Materials & Processes Engineering…hence Shot peening
A word on Safran Tech ➔ Safran Research Centre

New Materials & Processes

(R)evolutionary energetic architectures

Preservation and enhancement of Numerical data

Modelling

The factory of the future

New sensor development and miniaturization
CHALLENGES AND DEVELOPMENT TRENDS IN THE AIRCRAFT INDUSTRY

- **MORE EFFICIENT**
  - Stronger Materials
  - More performant coatings
  - Smarter design

- **GREENER & LIGHTER**
  - Gas Emission Reduction
  - Cleaner processes
  - Noise reduction
  - Lighter materials

- **LESS EXPENSIVE**
  - Competitive materials
  - Shorter production cycles

- **MORE RELIABLE**
  - More dependable quality control
  - More Health monitoring

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Forming and strengthening of Wing skins
Why “shot peening” is obsolete?

Peening? What makes it interesting?

Peening… Why?

Peening… What we don’t like

Designing with peening…

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Designing with peening…

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WHY IS « SHOT PEENING » OBSOLETE?
“Surface Compressive Straining Processes” instead of “Shot peening”?

Residual compressive stresses
Surface strain-hardening
Grain Refinement

Thread rolling
Low-Plasticity Burnishing
Cold Expansion
Laser Peening

Shot Peening
Conv., warm, cryo
US Peening
Vibro-Peening
Gravity Peening

Shot-based processes
Shotless processes
“Surface Compressive Straining Processes” instead of “Shot peening”?

- Shot Peening
- Conv., warm, cryo
- US Peening
- Vibro-Peening
- Gravity Peening

- Residual compressive stresses
- Surface strain-hardening
- Grain Refinement

- Thread rolling
- Low-Plasticity Burnishing
- Cold Expansion
- Laser Peening

- Shot-based processes
- Shot-less processes

- LOCALIZED PROCESS

- GENERALIZED PROCESS
Shotless Processes inducing geometry changes

- Cold Expansion
- Low Plasticity Burnishing
- Thread rolling

- P.S. Prevey and al., Case studies of fatigue life improvements by LPB in gas turbine engine applications, ASME Turbo Expo, Atlanta-Georgia, 2003


- Y. Huang and al., Improving the fatigue life of 2297-T87 aluminum-lithium alloy lugs by cold expansion, J.of Mat.Process.Tech., 249, 2017
PEENING...WHAT MAKES IT INTERESTING?

How does it change materials performance?
Is it surface compressive residual stresses?

- Depth of compressive stresses affected by SP
- Depth of maximum compressive stress
- Maximum compressive residual stresses
- Surface compressive stress

![Residual Stresses (RS) Vs Depth](image)

Fatigue crack propagation

Near-surface performance (Corrosion, wear, fretting, crack initiation)
Is it surface strain hardening/Cold working?

**EBSD – Udimet 720Li Ni-superalloy – Shot peened**

- **Is cold working a beneficial effect of peening?**
  - → Increase surface hardness
  - → Believed to be the reason of CRS relaxation: less CW, less CRS relaxation
  - → Produce a strain hardened layer (SHL)
  - → is SHL the controlling factor?

*Full Peak Width at Half Maximum (FWHM) Vs Depth*

*As Machined vs Shot Peened*

*Vickers Hardness vs Distance from edge in µm*

*D.J. Child and al., Acta Materialia, Vo.59, 2011*
Is it the near-surface microstructure modification?

- Nano-crystallization → Al-alloys, Ti-alloys and stainless steels

- Microstructure → Martensitic transformation of SS

**AA 6061**


**TA6V alloy**


**316L SS**

P.Kumar and al., IRJET, Vol.3, N.5, 2016

P.Peyre, Mat.Sc. And Eng., A280, 2000

**SP processed surface**

- Equiaxed nanograins layer
- Equiaxed ultrafine grains layer
- Elongated ultrafine grains layer
- Refined grains layer
- Low-strain matrix
- α phase
- β phase
- Matrix

**Microstructure characteristics in TA6V after SP**


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Material and process influence

**Residual stresses in In718**

![Graph showing residual stresses in In718](image)

- Shot peening (SP)
- Low Plasticity Burnishing (LPB)
- Laser Shock Peening (LSP)


**Residual stresses in TA6V**

![Graph showing residual stresses in TA6V](image)

- Shot Peened
- Gravity Peened
- LSP

*P. Prévey and al., Proceedings of the 17th Heat treating Conference, 1998*

**Depth of Compression vs. Peening Intensity**

![Graph showing depth of compression vs. peening intensity](image)

*R.N.Krishnan and al., IJCTA, Vol.9, N.37, 2016*
PEENING...WHY?
For what scope?

Almen fixtures on fan blades – Ref.: Guyson Corp.
What aircraft components performance can peening improve?

Fatigue

Crack initiation probability
Crack propagation rate

Corrosion

Fatigue-corrosion
Stress Corrosion Cracking
Localized corrosion

Surface functionality

Coatings performance
Tribological properties enhancement

Wear, Fretting, Pitting
Erosion
Fatigue improvement → How shot peening Mitigates defect impact on fatigue

✔ Reducing probability of crack initiation in materials defects

→ Mitigating Inclusions impact in U720 PM Ni-superalloy HP Turbine disk

Before Peening

After Peening


✔ Improving surface integrity

→ In-718 Ni-superalloy LP Turbine disk: Mitigating machining defects

Shot peened

Machined and shot peened

As machined

Shot peened

A.Chamanzar and al., Mat. Caract., Vol.132, 2017


**Corrosion and Stress-Corrosion resistance improvement → Impact of peening process**

- Peening process should be customized for lower Ra or shotless processes preferred
- TA6V Corrosion resistance in 3%NaCl improved by US peening

**Stress-corrosion cracking resistance**

- 300M SCC resistance in 3%NaCl improved by Low-Plasticity Burnishing

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D.Hornbag and al., Lambda Technology Tech Paper, #07ATC-104, 2007
Fatigue-corrosion improvement (Room and High-temperature)

→ 300M fatigue strength in 3%NaCl improved by Low-Plasticity Burnishing

→ High-strain hardened depth + low surface roughness are needed → Shot peening process control is paramount

P.S. Prevey and al., Proceedings of the 6th Aircraft corrosion workshop, 2004


P. Gabb and al., NASA/TM-215629, 2009
Peening for Coating

→ Mitigating fatigue debit due to plating 4340 HSS for aircraft applications

✓ Reduce fatigue debit linked to coating → Cr, Ni on high-strength steels; anodizing for Al alloys
✓ Delay excessive oxidation of TGO in TBC systems
✓ Counter tensile stresses due to coating/Substrate mismatch

→ Increasing cyclic oxidation life of engine blades TBC MrAlY/YSZ systems by decreasing TGO growth kinetics

Before Peening

After Peening

M.P. Nascimento and al., Materials Research, Vol.5, N.2, pp.95-100, 2002


Tribological properties → Fretting and Wear (peening improve H/E)

✓ Fretting fatigue at the engine disk/blade attachment (TA6V)

✓ Wear of aircraft steels (4340)

Before Peening

After Peening

Q. Yang and al., Wear, 2016

without shot peening

with shot peening

Tribological properties → Contact fatigue of gears

✓ Contact fatigue of carburized steel gears


![Graph showing residual stresses (MPa) vs. distance from the surface (mm)]

- Carburizing + shot peening (8A)
- Carburizing

<table>
<thead>
<tr>
<th>Stress intensity factor values, according to numerical computation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>With no residual stresses</strong></td>
</tr>
<tr>
<td><strong>$\Delta K_I$</strong></td>
</tr>
<tr>
<td><strong>$\Delta K_{II}$</strong></td>
</tr>
<tr>
<td><strong>$\Delta K_{eq}$</strong></td>
</tr>
</tbody>
</table>
WHAT WE DON’T LIKE?

YES, BUT…

Hugues Helicopter 369 accident - 2014
Surface finish comes with the package

✓ Roughness, surface defects

→ Reduce fatigue resistance effectiveness especially for LCF
→ Creates air turbulence In Aircraft engines where gas path passages have to be smoother (reduces fuel efficiency)


J.F. Loersch and al., ICSP1, 1969, 649-669
Instability of shot peening positive effects

- Relaxation of compressive residual stresses
  - Mainly due to mechanical cycling

Residual stresses Udimet 720Li @ 700°C
Thermomechanical Vs thermal relaxation

A. Evans and al., Int.J. of Fatigue, 27, 2005
Instability of shot peening positive effects

- Relaxation of compressive residual stresses

→ Material and temperature related

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature Limitation after Shot Peening (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-Superalloys</td>
<td>538</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>399</td>
</tr>
<tr>
<td>Ti-alloy</td>
<td>316</td>
</tr>
<tr>
<td>Low-alloyed steel</td>
<td>246</td>
</tr>
<tr>
<td>Aluminum Alloys</td>
<td>93</td>
</tr>
</tbody>
</table>

Source: AMS-S-13165

Residual stresses thermal relaxation in TA6V

Instability of shot peening positive effects

- Relaxation of compressive residual stresses

  ➔ Process dependant

LSP residual stresses are lower than shot peening’s but deeper and thermally more stable

LSP Cold work is 3X lower than shot peening’s BUT deeper
Instability of shot peening effects

✓ Instability of the Surface Hardened layer

→ recrystallization of the SHL during fatigue cycling

a) Ni-superalloy RR1000 As-Shot peened  b) After 144 fatigue cycles at 850MPa/700°C

Defects induced in real components

- SP poor control → surface « lifting », smearing on F18 parts
- Material folding at edges, chamfers of an engine component

7050 Al-alloy

Over-pressure or excessive time

Cross section

Rolled edge « Elephant tail » defect


Low angle

Ni-superalloy component
...and lack of homogeneity of shot peening?

✓ Expected near-surface changes? How to control homogeneity of strain worked layer on components?

- Inhomogeneity of the Strain Hardened Layer evidenced by EBSD on IN718DA – coverage control was OK!

✓ Coverage: Relies on human eye skills
✓ Non-homogeneity: Even when 100% coverage is met
✓ Shot peening can make NDI difficult by masking small cracks
DESIGNING WITH PEENING?

“Detection, Prediction and Avoidance”

Should peening stay just a “NICE TO HAVE”?"
What happens to peening induced conditions during operations?
Considerations for components design

- Mechanical surface stress relaxation
- Mechanical surface damage (erosion, FOD)
- Thermal surface stress relaxation (temperature, friction)
- Chemical surface damage (corrosion, oxidation)
What makes the design still conservative?...Incidents related to SP defects

**Non-homogeneous shot peening**

McDonnell Douglas Helicopters Hugues 369E (2011) → 7075-Al Tail rotor blade pitch horn

Boeing Co747-300 – Japan Air (2005) → Failure of steel LG Trunion fork during towing

**Peening surface fold**

Boeing 767- Air New Zealand (2002) → Ni-Superalloy Turbine disk failure at fit tree slot

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Working on design approaches → The chain that should be addressed

- OUTPUT 1 TO PEENING
- OUTPUT 2 TO POST PROCESSING
- OUTPUT 3 TO COMPONENT LIFE

• LIFE PREDICTION
• DAMAGE MONITORING FOR LIFE EXTENSION
Working on design approaches → The chain that should be addressed

**PEENING CHAIN**

- **OUTPUT 1 TO PEENING**
- **OUTPUT 2 TO POST PROCESSING**
- **OUTPUT 3 TO COMPONENT LIFE**

**COMPONENT LIFE**

- **LIFE PREDICTION**
- **DAMAGE MONITORING FOR LIFE EXTENSION**

**Peening Process Parameters**

- Residual Stresses
- Microstructure
- Work Hardening

**What the equipment provides:**

**Process control**

**How the Material Responds:**

**Mechanical and Metallurgical model**

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**External loads**

**Environment**

**FOD ...**
Working on **Process Control** → **Methods for process optimization**

→ **Statistical methods (Surface response)** – to address the impact of significant parameters of the process on process outputs

![Graphs showing response surface methodology](image)


→ **Big Data**: The use of historical data for Data Analytics
**Working on Process Control → Methods for process optimization**

→ **FE models – shot stream and impact modelling**

**Input**: media characteristics, equipment characteristics, part position and movement, process duration

**Output**: shots velocity and energy, impact density, angles of impact, *Almen intensity, coverage*

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J. Badreddine – Safran 2014-2016
Working on **Material response → How to predict it?**

**Input:** shots velocity and energy, impact density, angles of impact, *Almen intensity*, coverage

**Output:** Residual stresses, surface texture, near-surface microstructure modifications

Calculated $R_a$ for different coverage using different hardening laws


Numerical RS profile using FEM-DEM simplified simulation

*A.B.Edward, Procedia Manufacturing, V.7, 2017*

Calculated Plastic Equivalent Strain for different coverages and approaches

*S.M. Hassani, Procedia Engineering, V.10, 2011*
Working on Material response → from the unit cell to the real part

Some FE modelling approaches using unit cells

Working on improving reliability of the **inspection** process (Quality control)

- **Controlling surface quality**
  - Be able to spot surface defects produced by shot peening and related processes (folds, rolled edges, …)

- **Controlling coverage** → Going beyond human eye
  - Image analysis, others…

- **Easy ways to measure compressive RS in complex geometries**

*Measuring CRS in aircraft complex geometries?*
Working on design approaches for **life prediction** to account for surface enhancement procedures

- Need the “real stress field” of critical life-limiting areas in real parts geometries (→ CRS)
- Need impacted surface materials constitutive law (Appropriate testing!)
- Need to take into account all impacting surface engineering treatments
- Need to take into account not only fatigue but also the other influential environmental effects → corrosion, erosion, FOD, …
- Need to take into account near-surface microstructure modification → Metallurgical models
Working on improving diagnostics and monitoring of components (Structural Health Monitoring)

- Following compressive stresses relaxation to determine residual life → Abnormal loading can relax CRS in a non-predicted way!
  - Collecting data from embedded sensors (strain gages, AE sensors, …)
  - Developing algorithms to analyze sensors data and determine residual life (data analytics)
- Material response through controlling the changes of strain-hardened layer
  - Eddy current can spot surface texturing

Magnetic sensor mounted on a critical surface of a Landing gear component for overload detection

N. Goldfine and al., 2006 SEM Annual Conference

Y. Shen and al., Int. J. of Non Destr. Eval., V.29, 2010
In Conclusion…

✓ Shot peening was, is and will stay a mandatory special process for critical parts

✓ For the peening to be taken into account in the design, this threefold strategy is needed:

1. Prediction
   a. To increase the process reproducibility
   b. To predict the occurrence of defect in a given geometry
   c. To predict compressive stress relaxation during operation

2. Avoidance
   a. To avoid/decrease the probability of harmful effect occurrence
   b. To work on processes that produce stable compressive stresses
   c. To focus on processes that improve surface finish

3. Detection
   a. NDT to ensure right coverage of the components
   b. NDT for the detection of SP-related defects
   c. In-situ monitoring of compressive stress relaxation

✓ …and keep trying to understand…

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