Surface Technologies
Division

SAE Fatigue (Bloomington, MN)

Assessment of "As-Printed", Machined & Post Processed Ti-6Al-4V for Aerospace Applications

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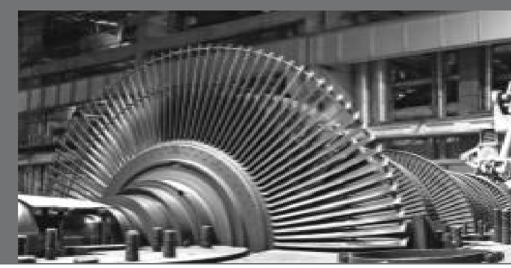

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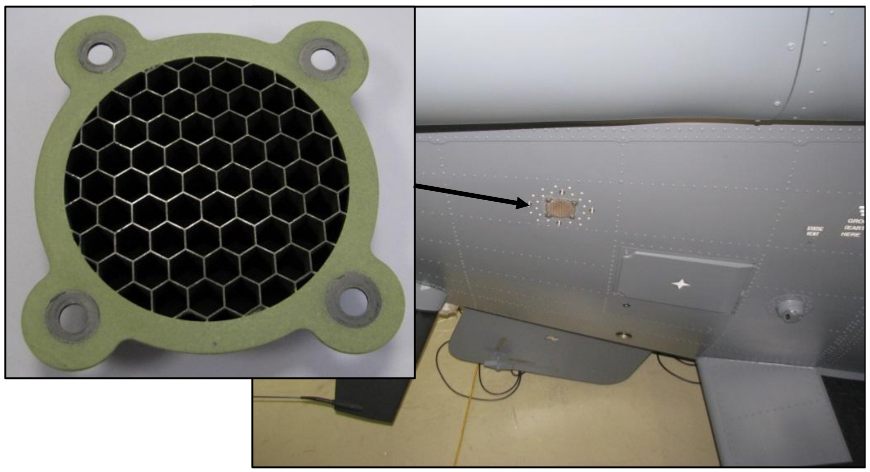
§ Motivation



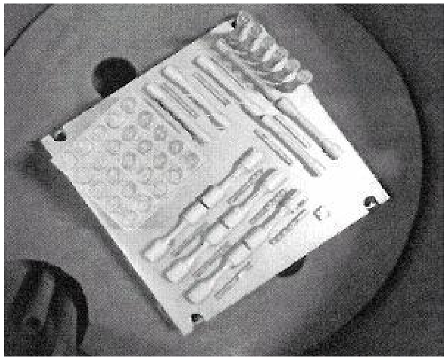
EMC Filter made of Ti-6Al-4V

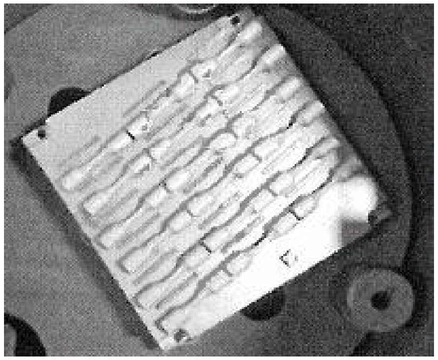
AgustaWestland/LEON ARDO AW 159 Helicopter

Introduction of ALM produced components first to replace parts which have a complex structure and are therefore difficult to produce by conventional production methods.

As these components are used in flying systems their static and fatigue properties must be investigated.

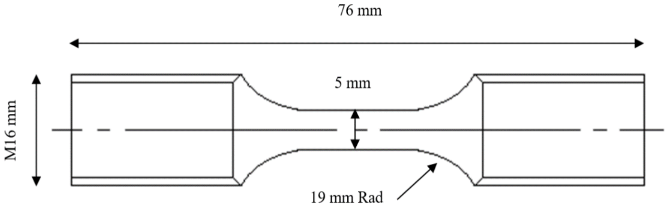
§ Material, Processing & Heat Treatment





Location of ALM Test Coupons on Build Platens

ALM Process:	Selective Laser Melting (SLM)
Material:	Ti-6Al-4V (AMS 4998)
Powder size:	50µm
Hot Isostatic Pressing:	924 ℃, 125 min, 100 MPa
Annealing:	700 ℃, 2 h
Tensile test:	EN 2002-1
Fatigue test:	axially - R 0,1 – 80 Hz
Residual stress:	XSTRESS 3000 – X-Ray
Roughness:	MarTalk GD 25

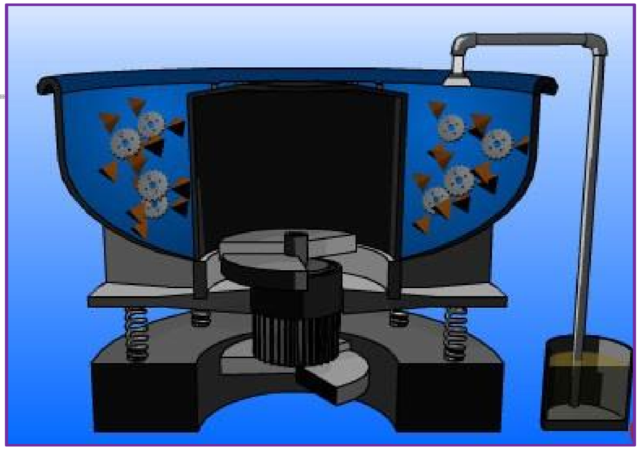


Vibrophore Fatigue Test Specimen Design

Batch	Vibrophore Fatigue Sample Identity	Post ALM Processing
A	AF (1 to 7 and 9 to 12)	Machined (Compact Engineering)
B	BF (1 to 10)	As Printed
C	AF (16, 27, 29, 31, 35, 37, 39, 44)	Shot Peened
D	N (15, 26, 32, 33, 34, 36, 38, 41)	Shot Peened & Superfinished

Post ALM Processing applied to the Different Batches

§ Tensile Properties

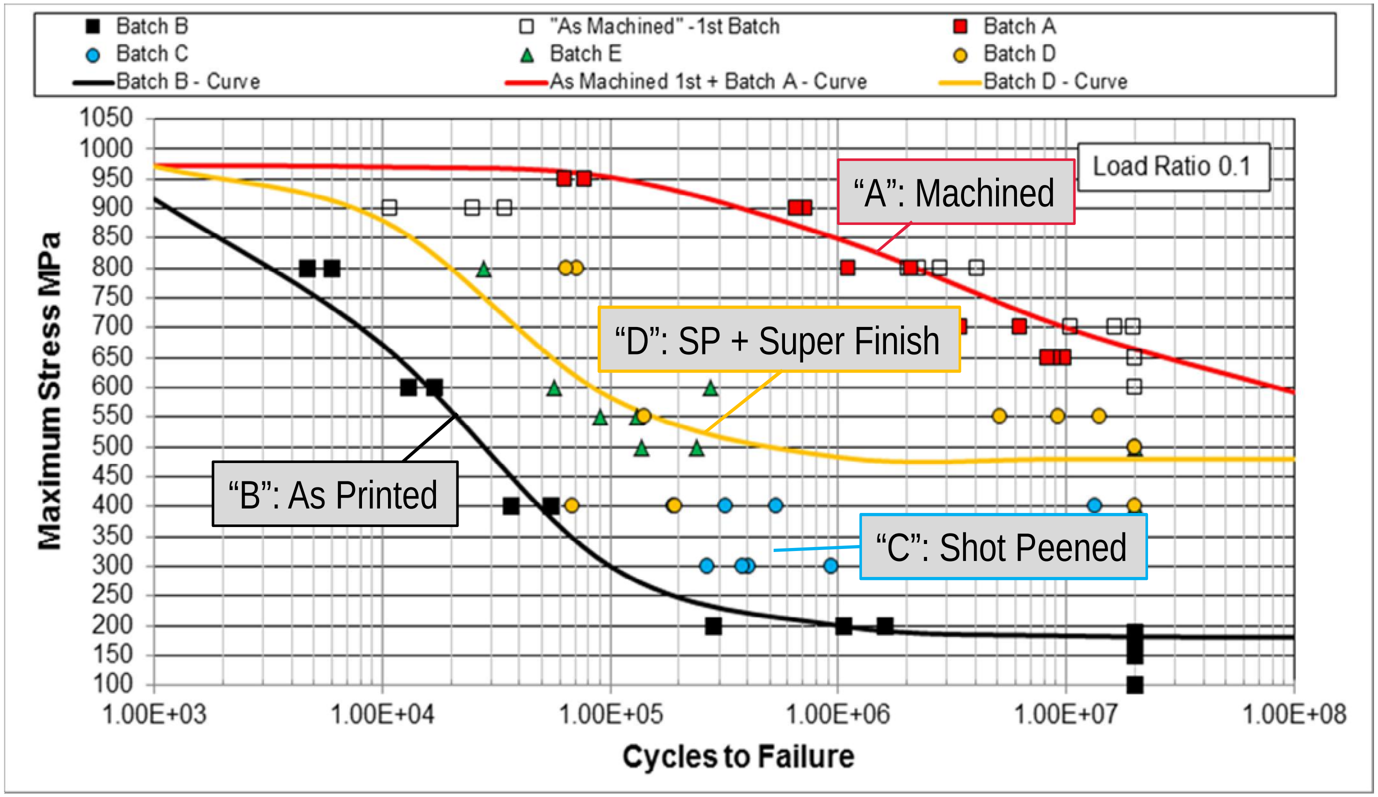


Processing Route (Build Direction)	Batch Identity	Specimen Identity	0.2% PS (MPa)	UTS (MPa)	Elongation (%)	RA (%)
Machined	A	AT1	-	985	16.1	50
		AT2	940	985	14.3	49
		AT3	931	985	14.3	47
		AT4	928	980	14.3	48
		Average	**933**	**981**	**14.8**	**49**
"As Printed"	B	BT1	900	946	8.9	32
		BT2	883	935	12.5	35
		BT3	-	937	8.9	41
		Average	**892**	**939**	**10.1**	**36**
Shot Peened	C	6	854	941	13.1	28
		10	849	969	11.6	28
		Average	**852**	**956**	**12.4**	**28**
Shot Peened & Superfinished	D	4	891	978	14.8	37
		5	885	970	13.3	28
		Average	**888**	**974**	**14.1**	**33**
British Standard TA11		**L**	**830 min**	**900-1160**	**8 min**	**25 min**
AMS 4999		**Z**	**765 min**	**855 min**	**5 min**	**NS**

All batches fulfill the specifications for wrought bar tensile properties regardless of production procedure and post ALM treatment

Typical specifications/values for wrought Ti-6Al-4V

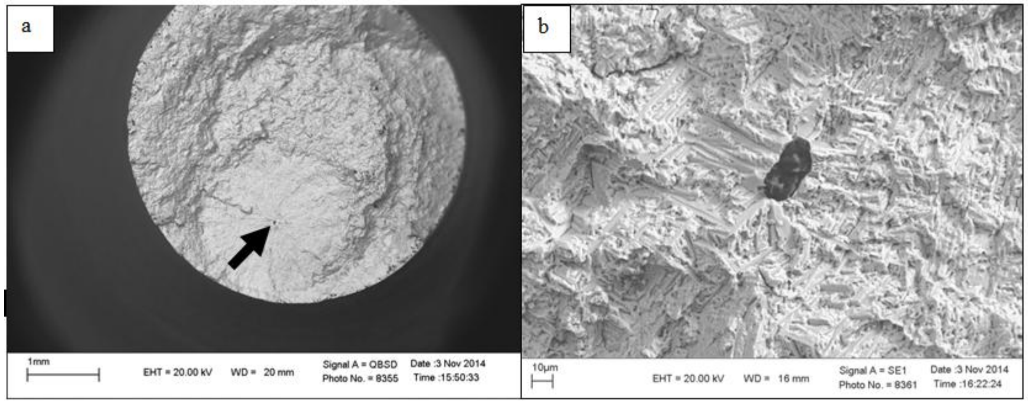
§ Overview of Fatigue Properties



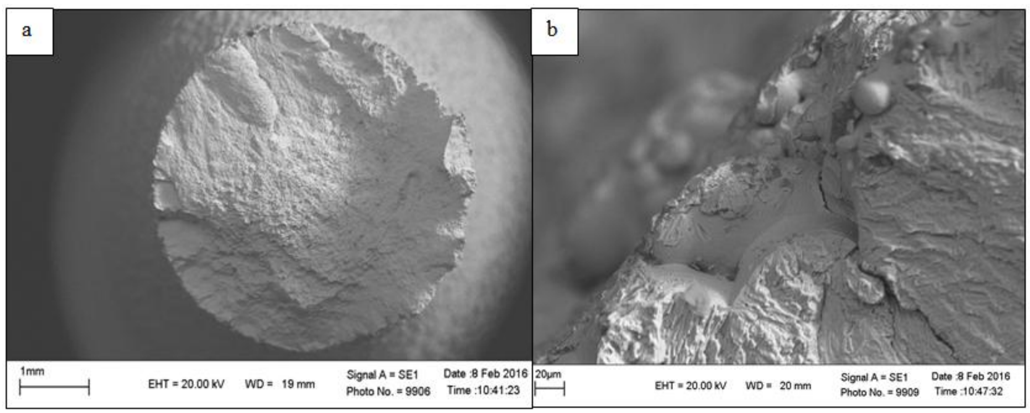
- Significant reduction in fatigue performance of the "As Printed" batch (black)
- Highest fatigue performance for the "As Machined" version (red)
- All Shot Peened and/or Super-finished specimens show improved fatigue performance compared to "As Printed" version.
  Best result for SP & Super-finished samples (orange)

S/N Curve of :
"As Printed" [Batch B],
"As Machined" [Batch A including previous ALM machined batch],
Shot Peened [Batch C],
Shot Peened/Super-Finished [Batch D]

- Fractographic/ Topographical Features I



Subsurface Initiated Fatigue Failure showing
a) Location (arrowed)
b) Cause: Pore



Surface Initiated Fatigue Failure showing
a) Location
b) Cause: Cold Shut (lack of fusion)

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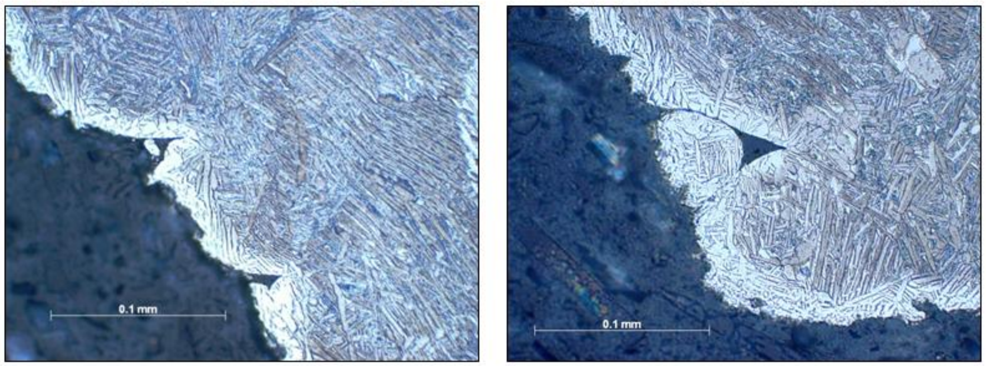
§ Fractographic/Topographical Features II



Micro-section taken through “As Printed” ALM showing Evidence of Surface Oxidation, Un-melted Powder Particles and Re-entrant Flaws/Notches

The fatigue performance of “As Printed“ specimens is reduced by:

- A far higher level of surface roughness
- The presence of tensile residual stress in the surface layer
- The presence of partially melted grains and unfused regions at the surfaces creating surface re-entrant angles/notches
- Evidence of surface oxidation (alpha case contamination)

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§ Shot Peening Parameters & Surface Roughness

Specimen Identification	Batch Identity	Post Processing Conditions	Surface Roughness [Ra] (µm) / (µ-in)
8	A	"As Machined"	0.88 / 35
13			0.99
12	B	"As Printed"	9.38 / 370
13			7.95
16	C	Peened (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	4.8 / 189
27		Peened (Shot: AF Glass, Intensity: 0.14 N, Coverage: 200%)	4.7
29		Peened (Shot: C Glass, Intensity: 0.19 N, Coverage: 100%)	3.7
31		Peened (Shot: C Glass, Intensity: 0.19 N, Coverage: 200%)	3
35		Peened (Shot: 110H, Intensity: 0.14 N, Coverage: 100%) + (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	5.1
37		Peened (Shot: 110H, Intensity: 0.14 N, Coverage: 200%) + (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	4.1
39		Peened (Shot: 230H, Intensity: 0.26 N, Coverage: 100%) + (Shot: AF Glass, Intensity: 0.15 N, Coverage: 100%)	3.2
44		Peened (Shot: 230H, Intensity: 0.26 N, Coverage: 200%) + (Shot: AF Glass, Intensity: 0.15 N, Coverage: 100%)	2.9 / 114
26	D	Peened (Shot: 110H, Intensity: 0.2-0.25 A, Coverage: 200%) + CASE Superfinished Short Time)	0.21 / 8.3
32		Peened (Shot: 110H, Intensity: 0.2-0.25 A, Coverage: 200%) + CASE Superfinished Extended Time)	0.22
36		Superfinished - MIC CASE Proprietary Process (Short Time)	0.37

- A reduction in the level of surface roughness "As Printed" ALM was achieved through the use of either steel shot or glass beads.
- Regardless of the type of shot or glass beads used, by increasing the level of coverage from 100% to 200% a (slight) reduction in surface roughness was obtained.
- By increasing the level of shot peening intensity a reduction in surface roughness was obtained.
- The C.A.S.E. (SP + Chemical Assisted Surface Enhancement) process reached the lowest roughness values

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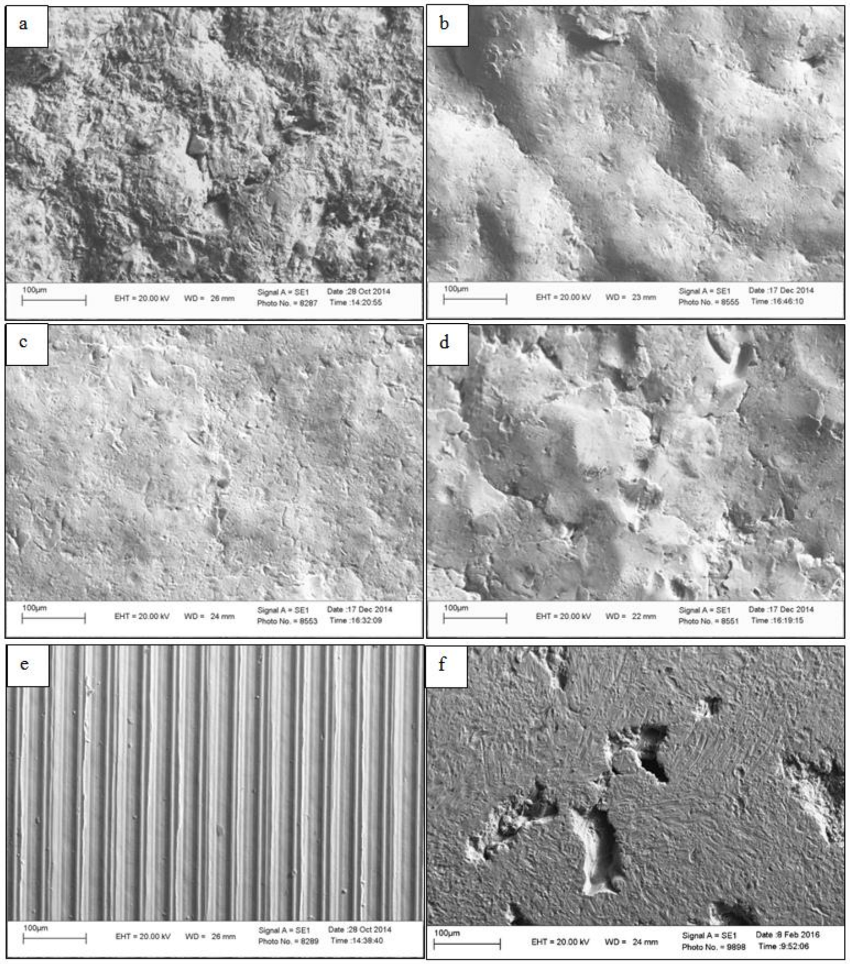
- Surface Topographical Features



a) “As Printed” ALM,
b) ALM + SP (AF Glass 0.14N 200%),

c) ALM + SP (230H 0.26N 200% + AF Glass 0.15N 100%),
d) ALM + SP (C Glass 0.19N 200%),

e) “As Machined” &
f) ALM + Superfinishing

§ Shot Peening Parameters & Residual Stress

Specimen Identification	Batch Identity	Post Processing Conditions	Residual Stress (Mpa / ksi)
8	A	"As Machined"	-367 / -53
13			-352
12	B	"As Printed"	+38 / 5.5
13			+39
16	C	Peened (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	-724 / -105
27		Peened (Shot: AF Glass, Intensity: 0.14 N, Coverage: 200%)	-714
29		Peened (Shot: C Glass, Intensity: 0.19 N, Coverage: 100%)	-745
31		Peened (Shot: C Glass, Intensity: 0.19 N, Coverage: 200%)	-802 / -116
35		Peened (Shot: 110H, Intensity: 0.14 N, Coverage: 100%) + (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	-937 / -136
37		Peened (Shot: 110H, Intensity: 0.14 N, Coverage: 200%) + (Shot: AF Glass, Intensity: 0.14 N, Coverage: 100%)	-1012 / -147
39		Peened (Shot: 230H, Intensity: 0.26 N, Coverage: 100%) + (Shot: AF Glass, Intensity: 0.15 N, Coverage: 100%)	-886
44		Peened (Shot: 230H, Intensity: 0.26 N, Coverage: 200%) + (Shot: AF Glass, Intensity: 0.15 N, Coverage: 100%)	-987
26	D	Peened (Shot: 110H, Intensity: 0.2-0.25 A, Coverage: 200%) + CASE Superfinished Short Time)	-726
32		Peened (Shot: 110H, Intensity: 0.2-0.25 A, Coverage: 200%) + CASE Superfinished Extended Time)	-759
36		Superfinished only - MIC Proprietary Process (Short Time)	-418 / -61

- ALM printed specimens show slight tensile stresses in the surface
- Machining removes and/or induces compressive residual stress
- All Shot peening call outs induces high compressive surface stresses whereas the highest have been measured in the combination of steel shot followed by glass
- The super-finishing process alone removes and/or induces compressive stresses in the range of "As Machined"

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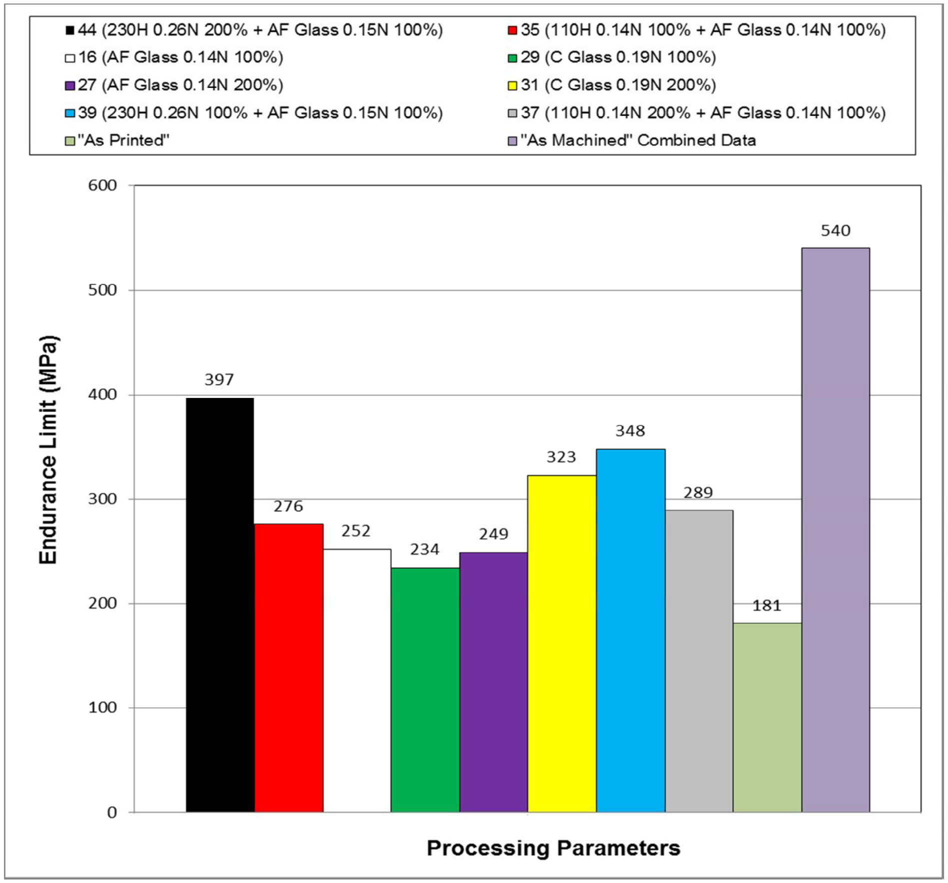
§ ALM - Influence of Shot peening on Fatigue

<u>Data trends:</u>

- The use of C or AF Glass increased the endurance limit of the "As Printed" ALM batch by appr. 30 %
- Steel shot increased the fatigue endurance by appr. 45 %
- The combination of steel shot followed by glass more than doubled the "As Printed" endurance limit

The higher the intensity, the larger the size of shot and the coverage that was employed the higher the resultant endurance limit

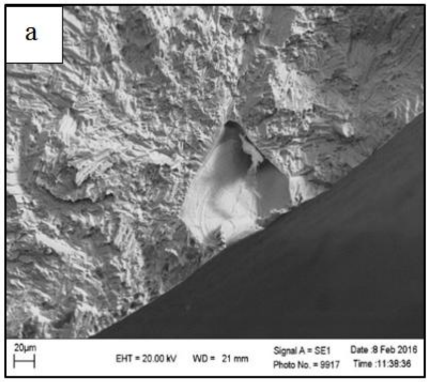


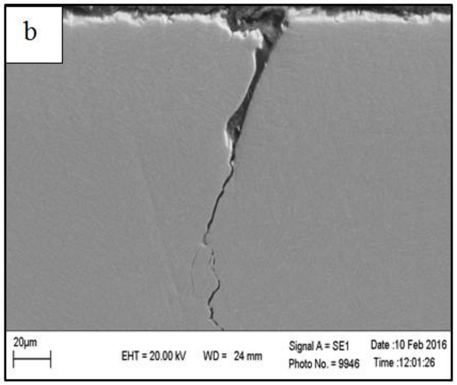
Influence of Shot Peening on Fatigue Endurance of "As Printed" ALM

§ ALM - Influence of Shot peening & Super-Finishing on Fatigue

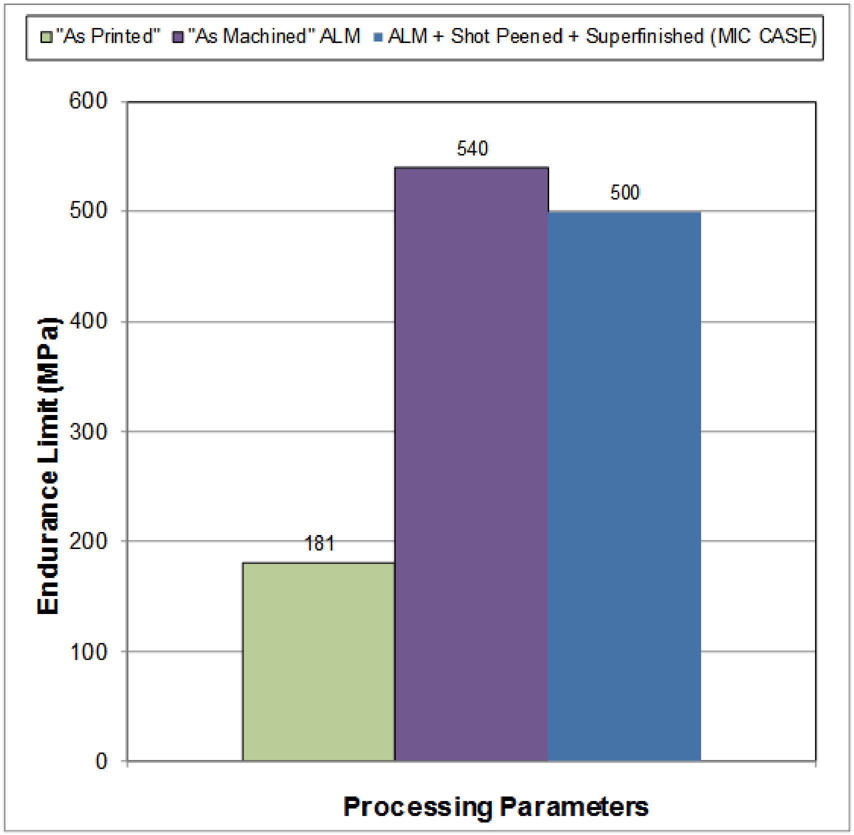
Data trends:

- C.A.S.E. (SP & super-finished) treated samples nearly reach the level of "As Machined"
- There is still a difference most likely due to the fact that by machining all the fatigue wise detrimental ALM surface features were removed





Surface Failure from
a) Cold Shut/Oxide Film and
b) Micro-section showing a Fatigue Crack Initiating from a Cold Shut



Influence of Shot Peening & Superfinishing on Fatigue Endurance when Compared to "As Printed" and "As Machined" ALM

- Summary
  - When compared to the “As Machined” ALM produced fatigue samples the “As Printed” samples exhibited a substantial loss in fatigue life.
  - The fatigue life of the “As Printed” ALM can be increased by using shot peening, super-finishing or a combination of both post processing techniques.
    The greatest improvement in fatigue was achieved by the use of shot peening combined with super-finishing.
  - However, although substantial improvements in fatigue endurance are possible, fatigue endurance cannot be restored to the “As Machined” condition largely due to the fact that ALM processing related (mainly sub-surface) failures are still present.

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