Friction Stir Additive Manufacturing as a potential route to achieve high performing structures

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Presentation outline

- Grand challenges confronting metal based additive manufacturing
- An overview of FSAM & where it fits best
- Seed results: Fabrication of high performance light-weight (Mg & Al based) alloys by FSAM
- Potential Application I: Integrated stringer assemblies on a skin panel fabricated by FSAM for aircraft fuselage
- Potential Application II: FSAM for fossil & nuclear energy applications
- Potential Application III: Functional & gradient materials by FSAM and listing of other potential applications for aerospace & energy industries
- Laser-FSAM hybrid & mini-sample testing capabilites

Chronological evolution of metal based additive technologies and key challenges

Current limitations and challenges (Fourfold)

Scale of production:
1) Build volume
2) Layer thickness

Limits part size (few mm³ and microns)

Economic consideration:
1) High production cost
2) Low production rate

Cost of product, delivery time

Mechanical property:
Solidification microstructures leading to property knockdown

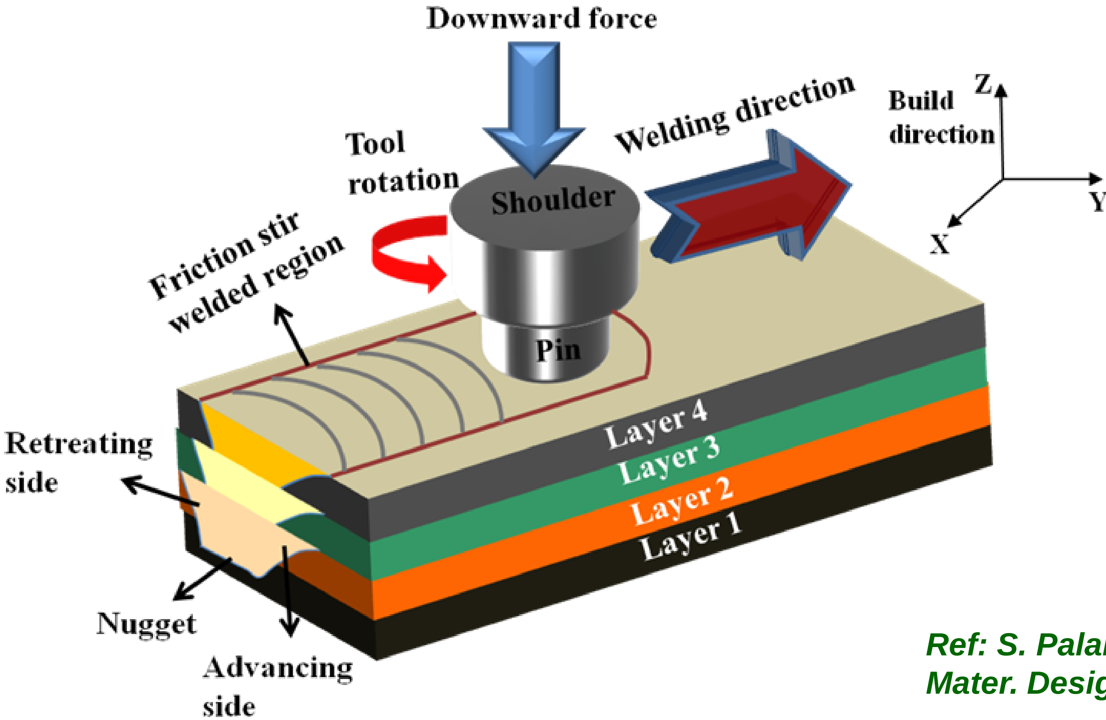
Part lifetime and efficiency

Environment & Energy
1) Usage of shielding gas by fusion process
2) High power requirement

Key issues		➢ Severe overhangs ➢ Solidification microstructure ➢ Mechanical properties	➢ Post processing ➢ Time consuming ➢ Mechanical properties	➢ Post processing ➢ High production cost ➢ Properties	➢ Post processing ➢ Low build rate	➢ Foil preparation ➢ Low build volume ➢ Mechanical properties	➢ Post processing ➢ High operating cost	➢ Mechanical property ➢ Low build rate	➢ Surface quality
Build volume (mm³) **Build rate (mm³/s)**		- 300x300x300 - 60	- 750x400x400 - 2000	- 250x250x250 - 4-16	- 1500x800x800 - 85	- Small - Slow	- 250x250x325 - 2-8	250x250x 280 - 0.5-5.5	200x200x 350 - 45-66
Layer thickness		120 µm	280-500 µm	20-100 µm	140 µm	Less	20 -80 µm	20 – 80 µm	50 µm
Materials studied		Steels, Nickel based super alloy, Inconel, Titanium, Cobalt	Steel, Bronze	Steels, Inconel, Titanium, Cobalt, Aluminum(Al)	Steels, Wasp alloy, Titanium(Ti)	Aluminum alloys	Steels, Titanium, Cobalt, Aluminum	Precious metals, Steel, Titanium, Aluminum	Copper, Beryllium, Steels, Ti, Al, Ni
Advantages		➢ Can use composite powder mixture ➢ High cooling rate	➢ Complex geometry is achievable	➢ Complex geometry is achievable	➢ Neutral gas ➢ Better property in comparison to castings	➢ Solid state ➢ Multi material structure ➢ Environment friendly	➢ Multi material structure	➢ High quality finishing ➢ Reduction in stress	Faster builds in comparison to DMLS and SLM
Temporal evolution of metal based additive technology	Selective laser sintering Laminated object manufacturing (LOM)	Laser engineered net shaping (LENS) Laser additive manufacturing (LAM)	Digital part metallization (Prometal)	Selective laser melting (SLM)	Easy clad Direct metal deposition (DMD), Similar to LENS with higher build capacity	Ultrasonic consolidation (UAM)	Direct metal laser sintering (DMLS)	Laser cusing	Electron beam melting (EBM)
	1991,92	1997,98	1999		2000	2001	2003	2004	2006

Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

Friction stir additive manufacturing (FSAM): Process description



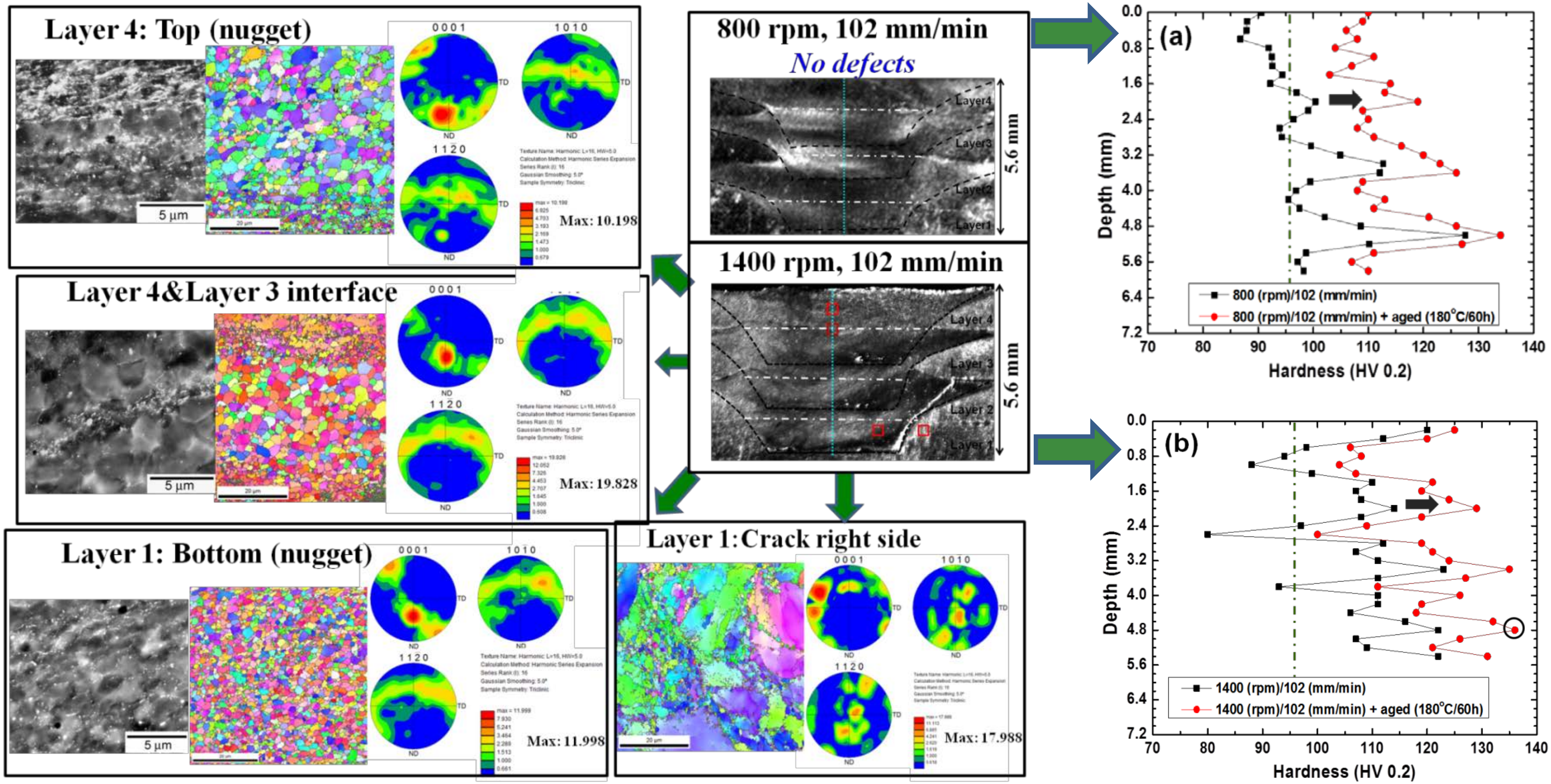
Friction Stir- Laser Hybrid Machine at CFSP

Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

- Non-consumable rotating tool with a custom designed pin and shoulder is inserted into the surfaces of sheets or plates to be joined and traversed along the joint line
- Joints are produced in solid state and involve no melting.
- Final thickness of the joint depends on the: (i) thickness of the sheets/plate, and (ii) number of assembly stages/layers
- In contrast to the cast approach in fusion based techniques, ***FSAM leads to wrought microstructures***

CFSP Center for Friction Stir Processing

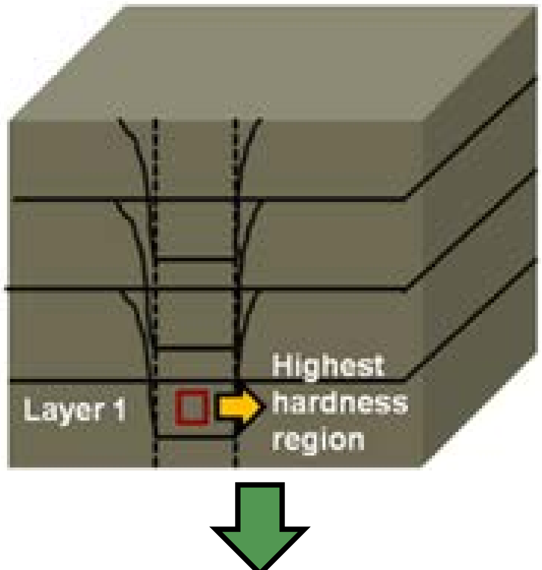
Seed results: High performance Mg-Y-Nd alloy built by FSAM

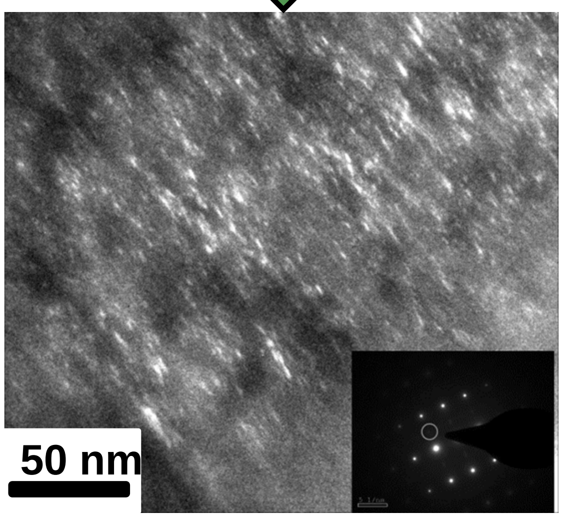


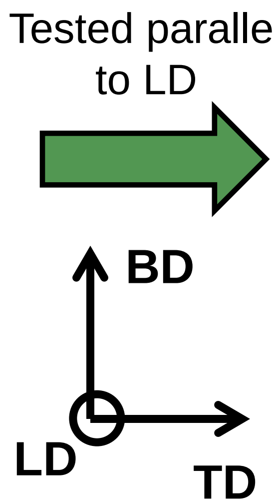
Ref: S. Palanivel, N. Phalgun, B. Glass, R.S. Mishra, Mater. Design, 65 (2015), 934-952

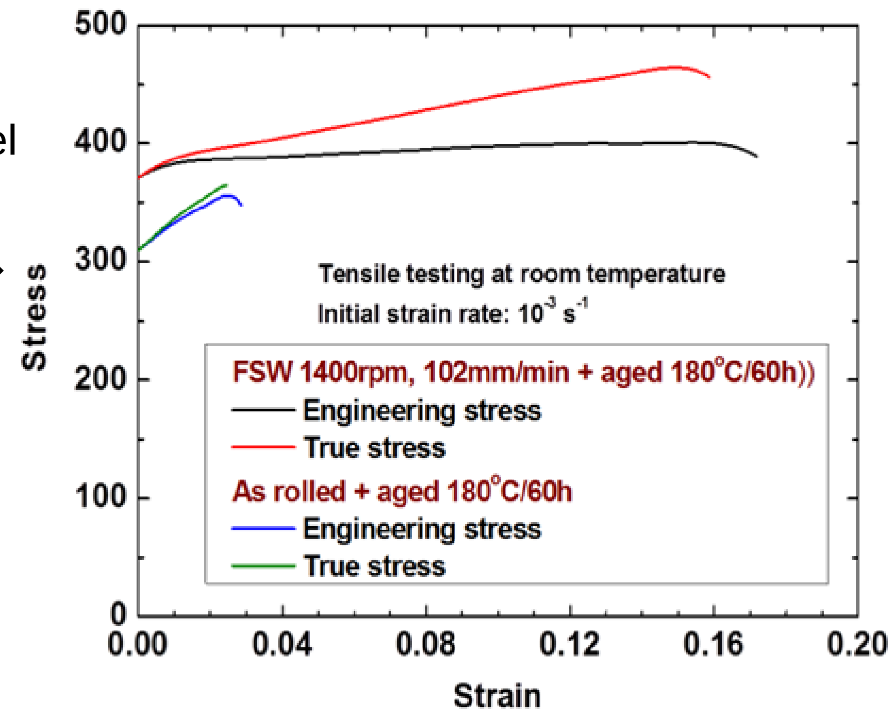
- ***Hardness- 135 HV (Built+aged). These values are similar to Al 2XXX alloys!***
- Maximum hardness achieved by conventional techniques/heat treatment routes is 110-120 HV

Seed results: High performance Mg-Y-Nd alloy built by FSAM





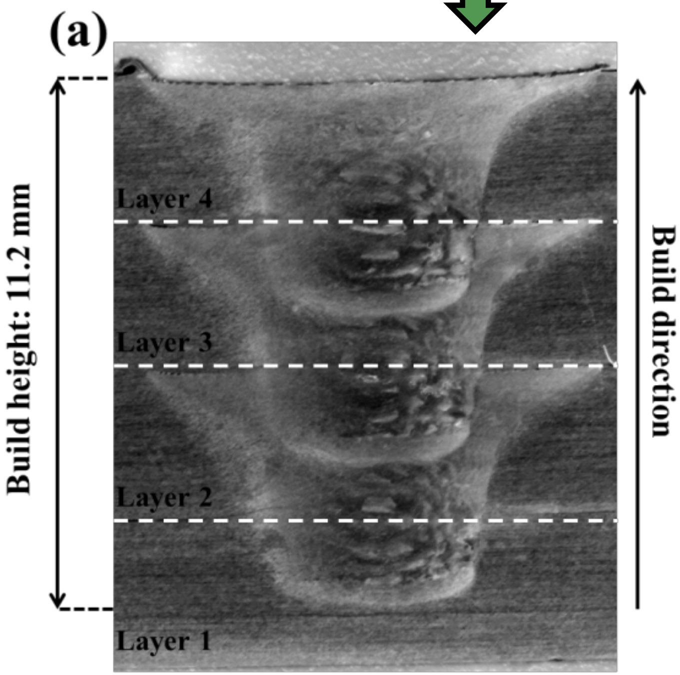


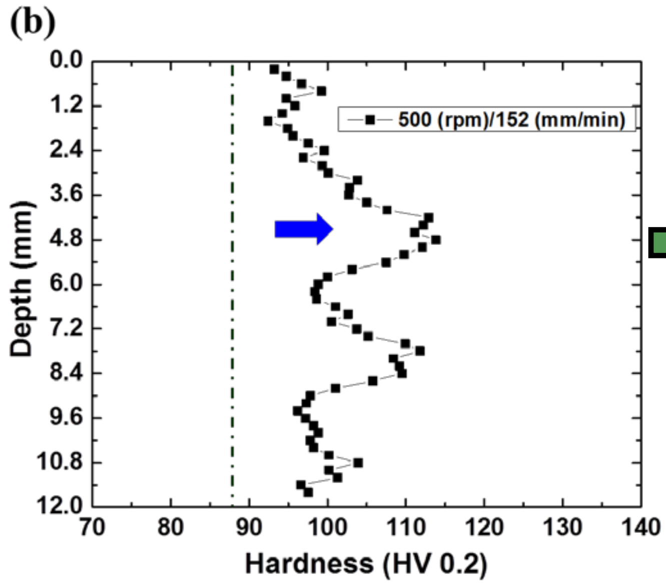


- Higher strength and ductility
- Fine (2-7 nm) and uniform distribution of strengthening precipitates lead to high strength in FSAM + aged specimen
- ***Properties achieved are much higher than the starting material (T5)***

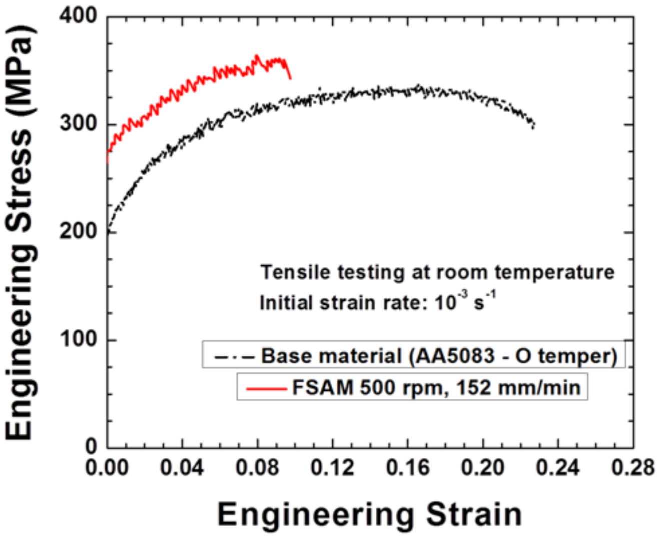
Seed results: High performance AA 5083 alloy built by FSAM

Fully consolidated build fabricated at rotation and tool speed of 500 rpm and 152mm/min





In comparison to base material, hardness in build is higher by 18%



Tested parallel to build direction

Condition	Yield Strength (MPa)	Tensile strength (MPa)	% E
Base Material	190	336	22.5
FSAM build	267	362	10

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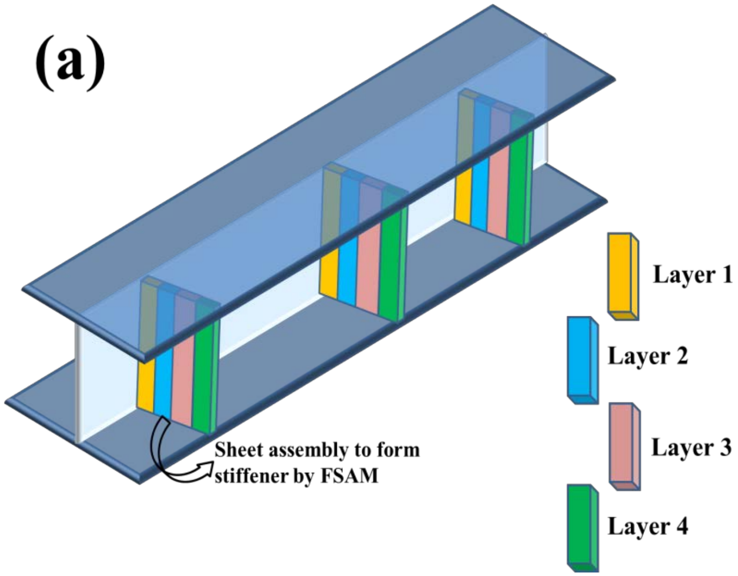
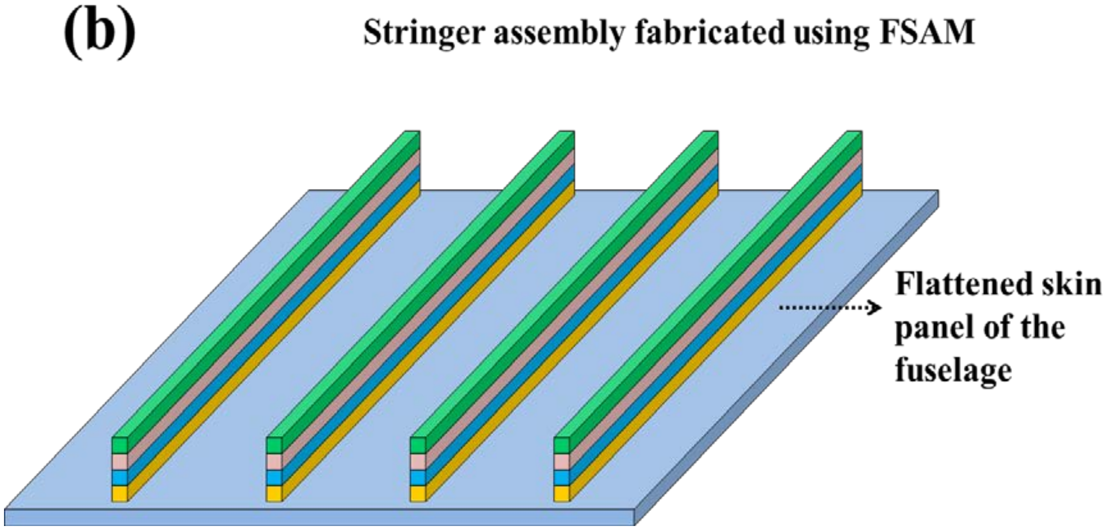
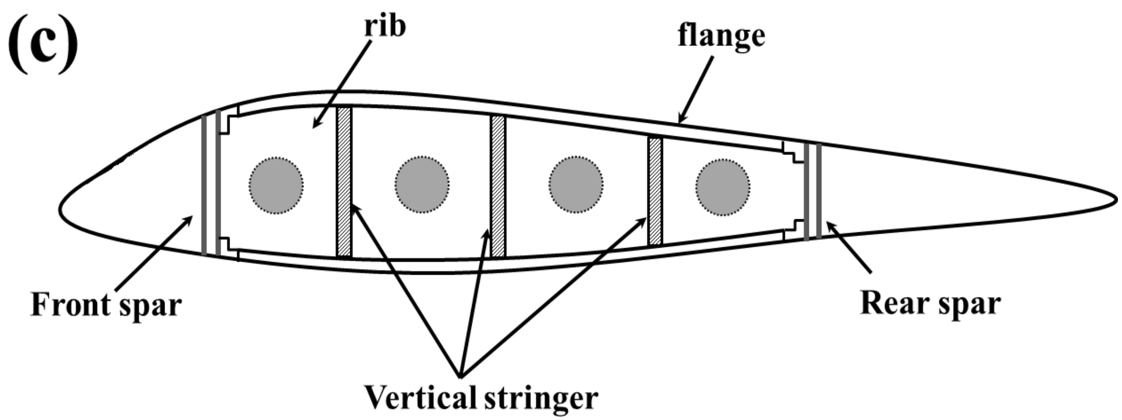
S. Palanivel, H. Sidhar, R. S. Mishra, JOM 67 (3) (2015), 616-621.

Potential application I: strong stiffener/stringer configurations for aerospace by FSAM







- FSAM can also be extended for designing and manufacturing longerons in skin panels

S. Palanivel, H. Sidhar, R. S. Mishra, JOM 67 (3) (2015), 616-621.

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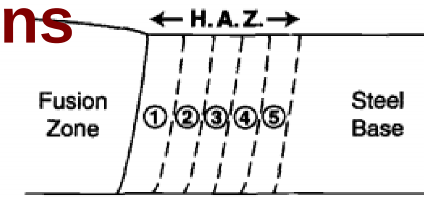
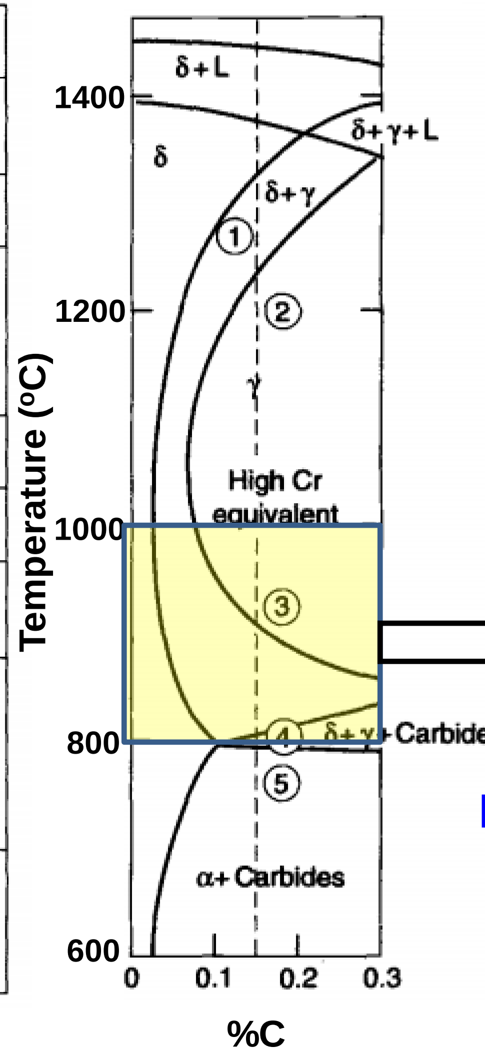
Drive behind FSAM for energy — physical metallurgy of ferritic-martensitic steels used in fossil & nuclear applications

Precipitate phases and their distribution in ferritic-martensitic steels

Precipitate Phase	Crystal Structure and Lattice Parameter	Typical Composition	Distribution of Precipitates
$M_{23}C_6$	fcc a =1.066 nm	$(Cr_{16}Fe_6Mo)C_6$ $(Cr_4Fe_{12}Mo_4Si_2WV)C_6$	Coarse particles at prior austenite grain and martensite lath boundaries and fine intra-lath particles
MX	f.c.c. a = 0.444-0.447 nm	NbC, NbN, VN, (CrV)N, Nb(CN) and (NbV)C	Undissolved particles and fine precipitates at martensite lath boundaries
M_2X	Hexagonal a = 0.478 nm c = 0.444 nm	Cr_2N, Mo_2C and W_2C	Martensite lath boundaries (Cr_2N and Mo_2C); prior austenite grain boundaries (Mo_2C); intra-lath (Mo_2C and W_2C); δ-ferrite in duplex steels [$Cr_2(CN)$ and $(CrMo)_2(CN)$]
Z-phase	Tetragonal a = 0.286 nm c = 0.739 nm	(CrVNb)N	Large plate-like particles in the matrix after creep straining at 600°C
η-carbide	Diamond cubic a = 1.07-1.22 nm	M_6C $(Fe_{39}Cr_6Mo_4Si_{10})C$	Prior austenite grain and martensite lath boundaries and intra-lath
Vanadium carbide	f.c.c. a = 0.420 nm	V_4C_3	Low number density in matrix
Laves	Hexagonal a = 0.4744 nm c = 0.7725 nm	Fe_2Mo Fe_2W and $Fe_2(MoW)$	Prior austenite grain and martensite lath boundaries and intra-lath; δ-ferrite in duplex steels
Chi (χ)	b.c.c. a = 0.892 nm.	$M_{18}C$ or $Fe_{35}Cr_{12}Mo_{10}C$	Intra-martensite lath; δ-ferrite in duplex steels





ion Zone (FZ): $T > T_m$

at - Affected - Zone (HAZ) [as-welded]:

Region 1	$T_m > T > T_{\gamma\delta}$	$\gamma + \delta \rightarrow$ Martensite + δ
Region 2	$T_{\gamma\delta} > T > A_{c3}$	Coarse grained $\gamma \rightarrow$ Martensite
Region 3	$T_{\gamma\delta} > T > A_{c3}$	Fine grained $\gamma \rightarrow$ Martensite
Region 4	$A_{c3} > T > A_{c1}$	$\gamma \rightarrow$ Martensite + Overtempered Martensite
Region 5	$A_{c1} > T > T_T$	Overtempered Martensite

ere T = temperature achieved during welding

T_m = melting point of steel

$T_{\gamma\delta}$ = temperature at which $\gamma \rightarrow \delta$ transformation is complete on heating

T_T = original tempering temperature of steel

A_{c1} = temperature at which $\alpha \rightarrow \gamma$ transformation starts on heating

A_{c3} = temperature at which $\alpha \rightarrow \gamma$ transformation is complete on heating

FSAM range

↓

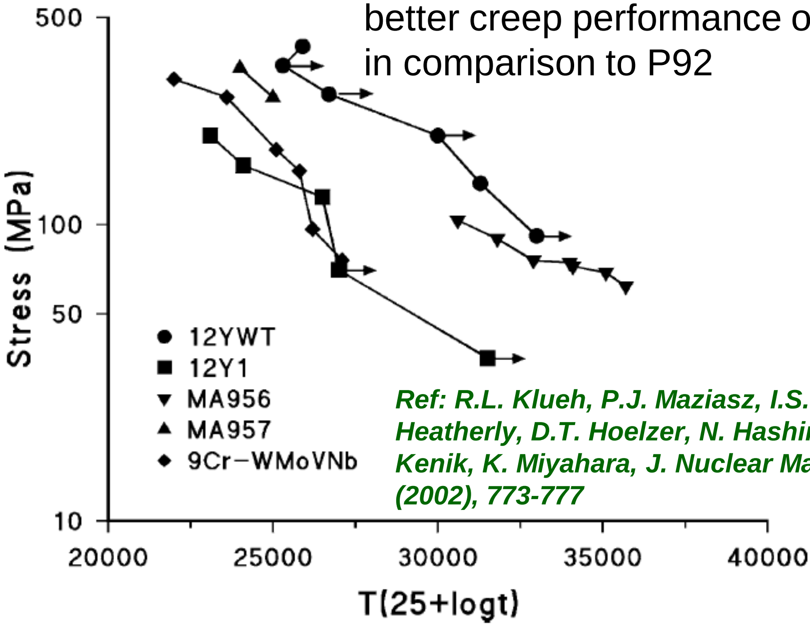
No δ phase,
Finer prior austenite grain size

↓

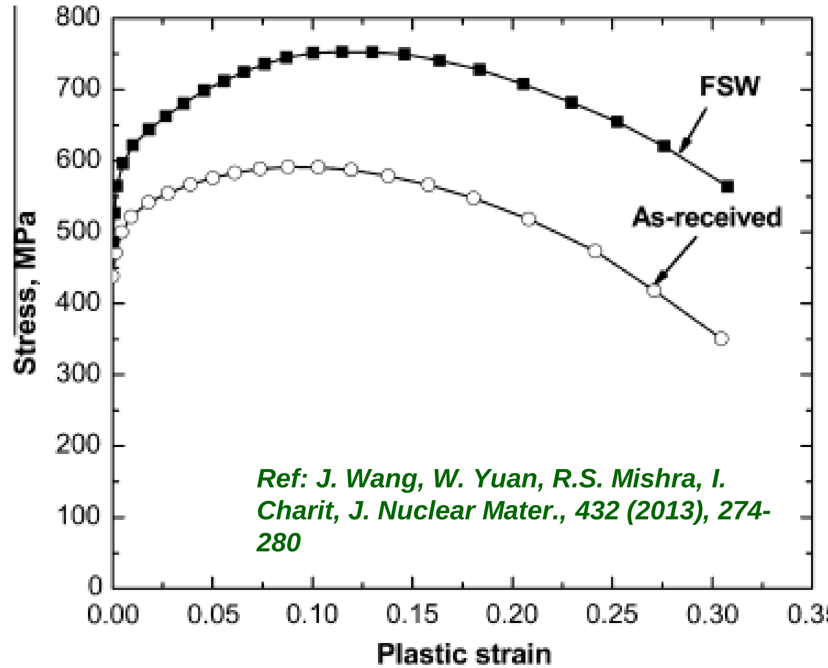
Better mechanical properties??

Drive behind FSAM for energy

Larson–Miller diagram showing better creep performance of MA956 in comparison to P92



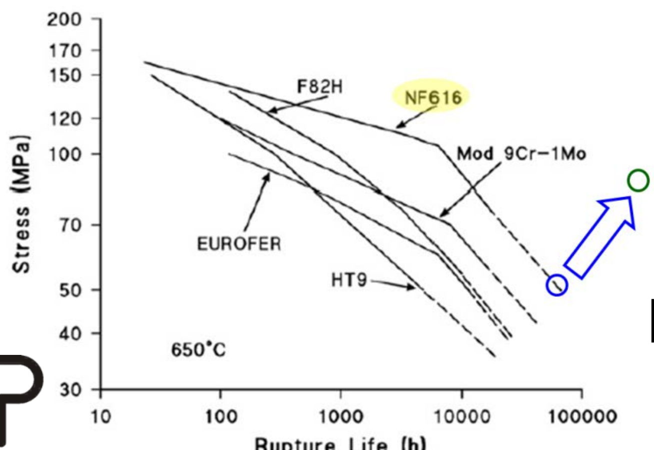
Ref: R.L. Klueh, P.J. Maziasz, I.S. Kim, L. Heatherly, D.T. Hoelzer, N. Hashimoto, E.A. Kenik, K. Miyahara, J. Nuclear Mater., 307 (2002), 773-777



Ref: J. Wang, W. Yuan, R.S. Mishra, I. Charit, J. Nuclear Mater., 432 (2013), 274-280

- ***Grain refinement & higher dislocation density after friction stir welding resulted in higher RT strength***

Condition	As-received	FSW
YS (MPa)	493 ± 17	574 ± 17
UTS (MPa)	591 ± 4	736 ± 14
UE (%)	8.1 ± 1.2	11.2 ± 1.1
E (%)	28.5 ± 1.9	30.7 ± 1.3



Increase creep strength (?) and rupture life by adding MA956 stringers to P92 steels using FSAM

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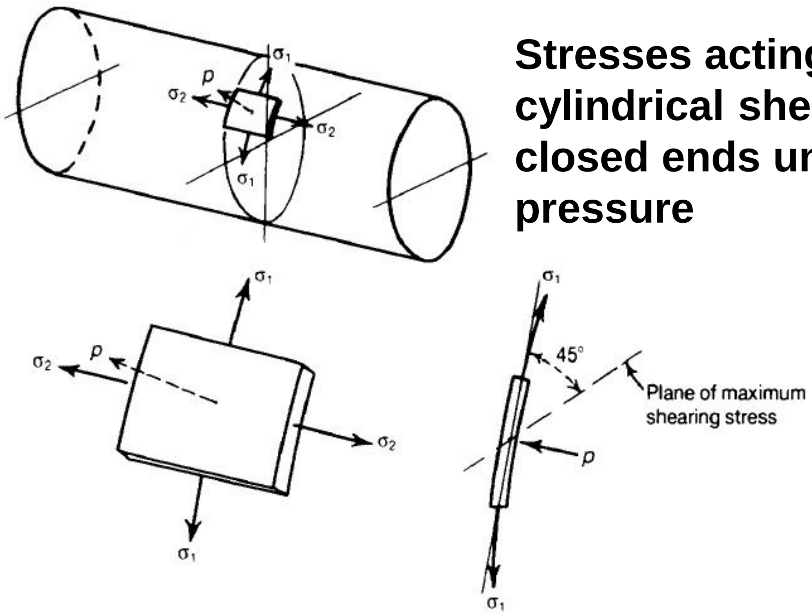
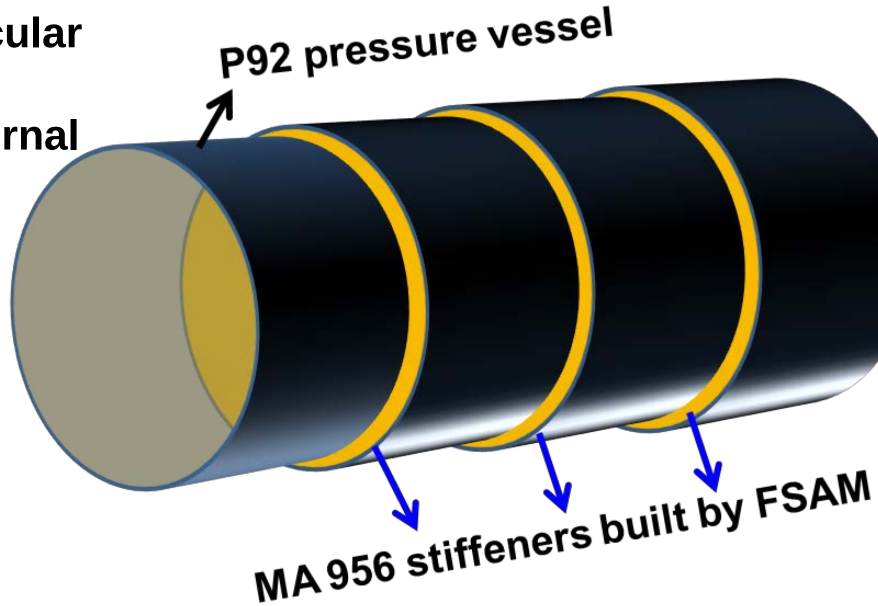
Potential application II: Architecting creep resistant structures by FSAM for fossil & nuclear sectors

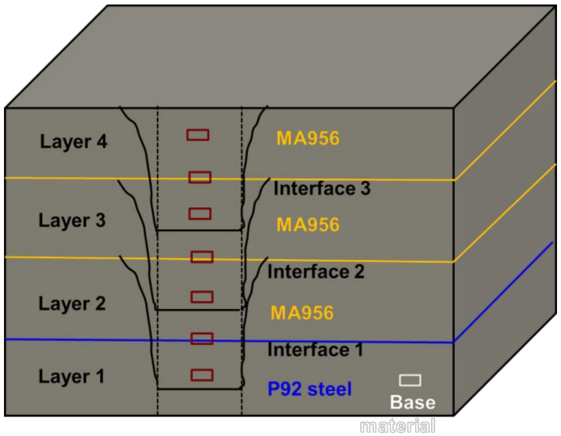


Stresses acting on circular cylindrical shell with closed ends under internal pressure



Schematic cross-sectional view of stiffened MA956 assembly over P92

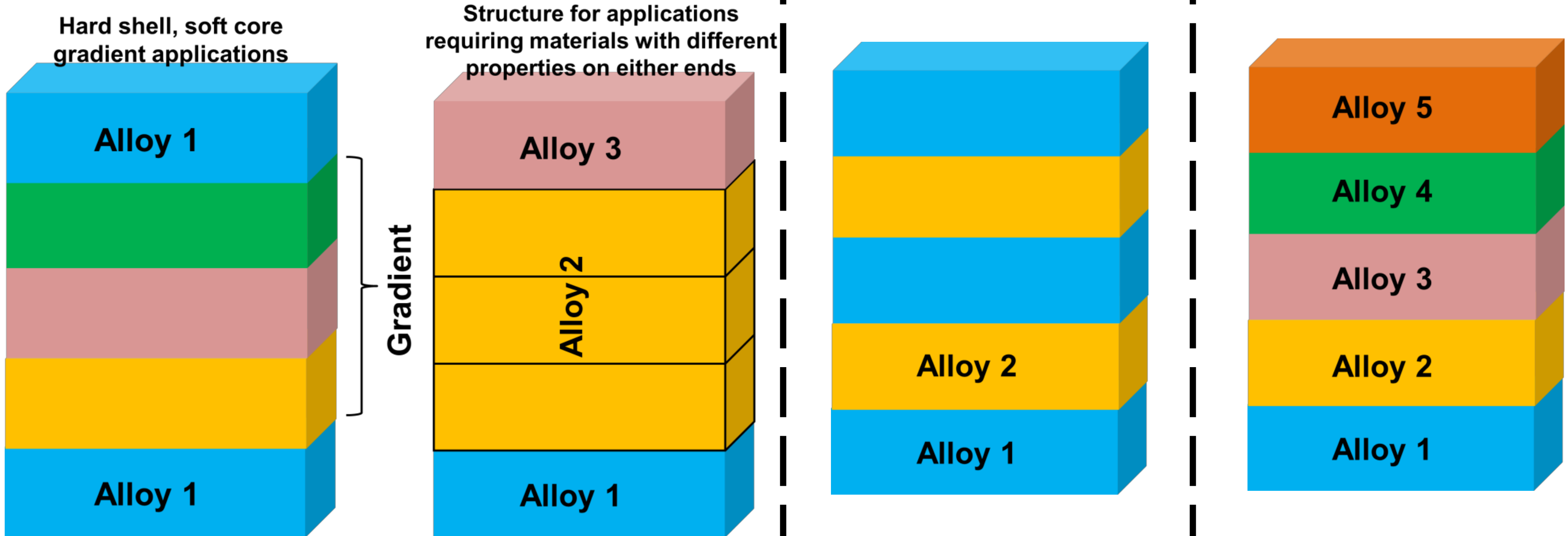
Schematic of MA956 stiffener rings on P92 steel for enhanced creep resistance



- Addition of partial or full ring stiffeners for pressure vessels to increase their lifetime
- Selection & design of the stiffening material needs to be in such a way that creep and internal stresses are accommodated by the built stiffener

Potential application III: Functional & gradient materials by FSAM for other applications

Conceptual schematic showing few possible configurations



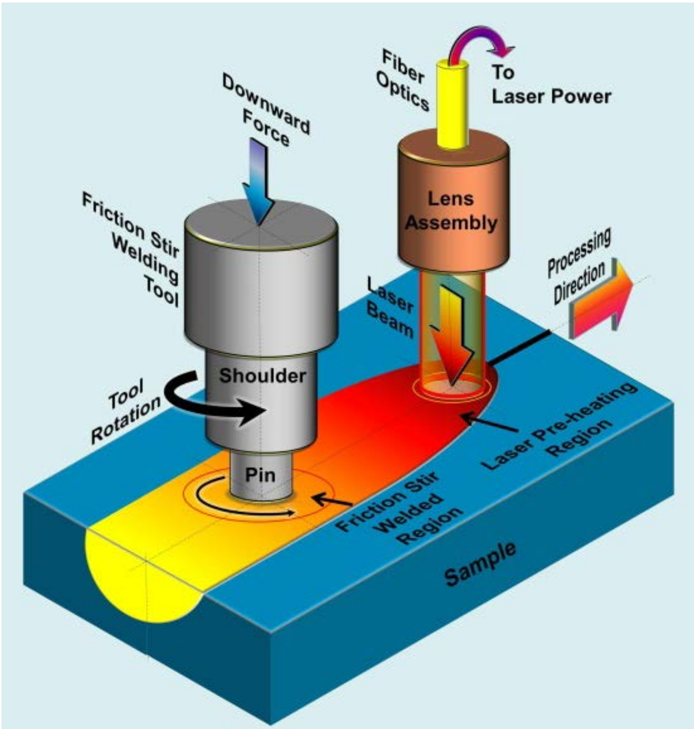
Sandwiched structure with a gradient | Alternating gradient structure | Fully gradient structure

➢ FSAM of composite materials

FSAM is a potential route to customize build performance by controlling microstructure

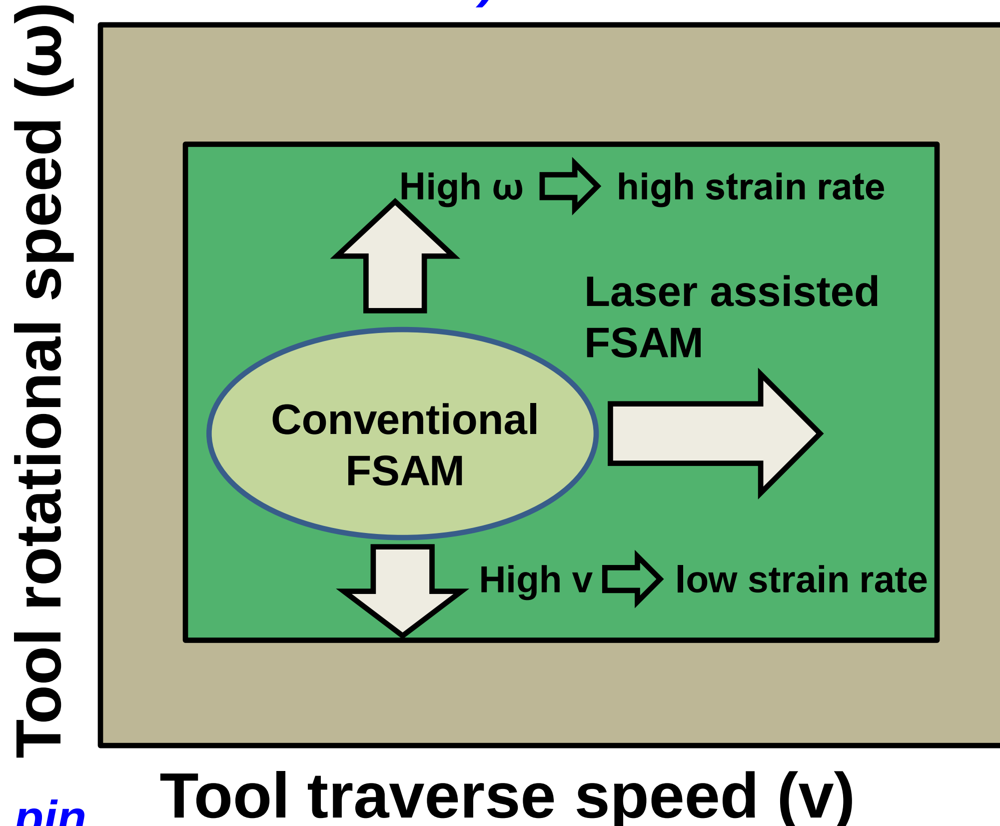
Laser assisted FSAM for reduction of forces and greater processing window

Pre-FSAM thermal treatment



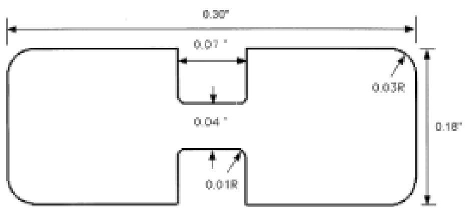
Preheating by laser source leads to softening of the material ahead of the pin and reduction of tool forces

Expansion of processing window by decoupling heat (greater control on microstructure)

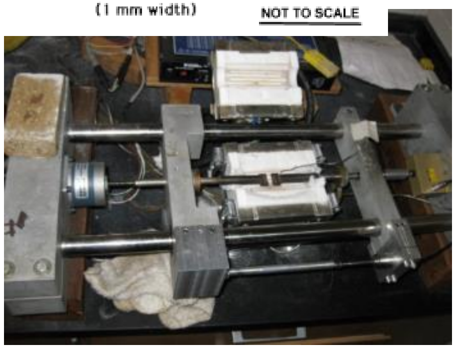


Mini testing capabilities to support FASM

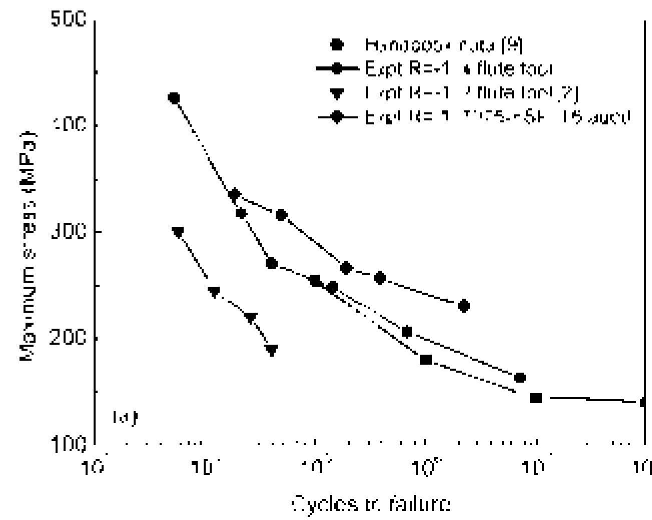
Drawing DARPA 01



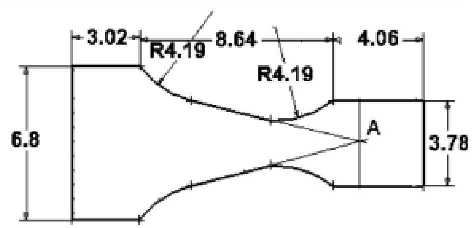
SMALL TENSILE SPECIMEN DIMENSIONS
(1 mm width)
NOT TO SCALE



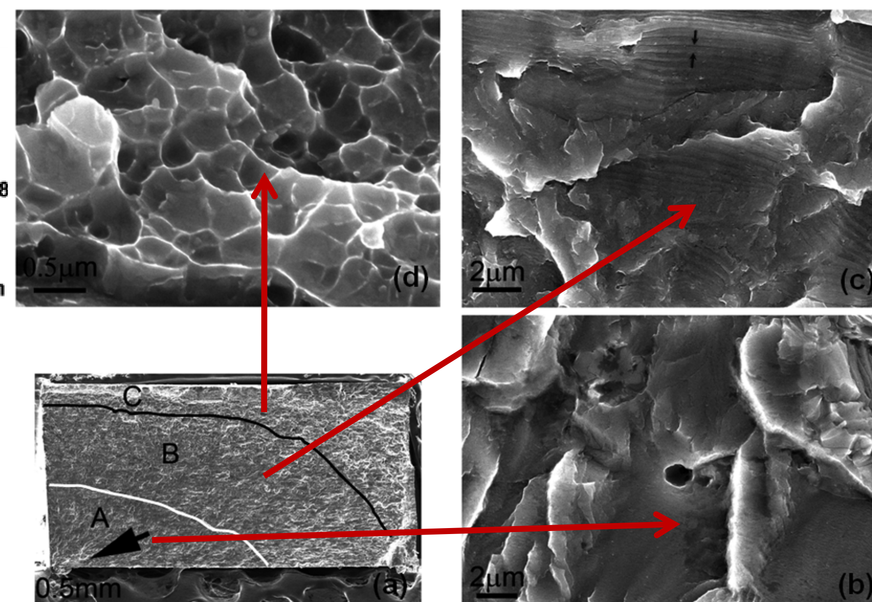
Mini-fatigue of 7075-T6



Mini-Fatigue



All dimensions in mm



- ***Can FSAM be an effective technique for production of high performance components?***
  - ***It certainly appears promising for simpler geometries***
  - ***Looking for collaborative opportunities to explore more material/design combinations***

Thank you

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