LES MÉTAUX AMORPHES,

UNE INNOVATION DE RUPTURE DANS LE DOMAINE DES MATÉRIAUX ET DE LA FATIGUE

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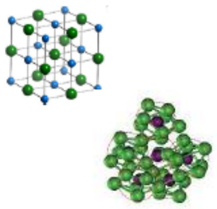
BULK METALLIC GLASSES

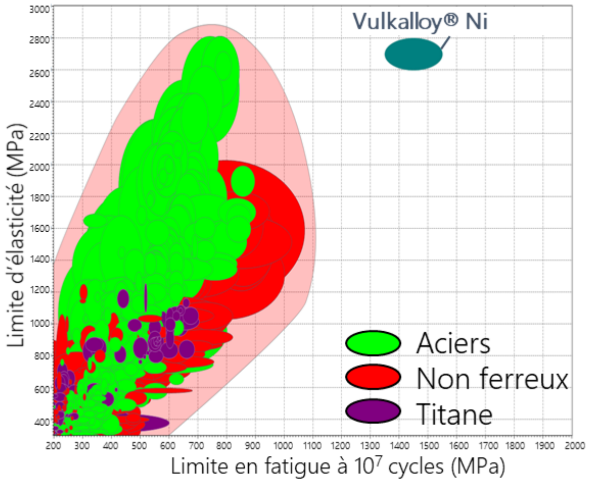
Microstructure

- Common alloys ►crystalline microstructure
- Bulk Metallic Glass ►amorphous microstructure

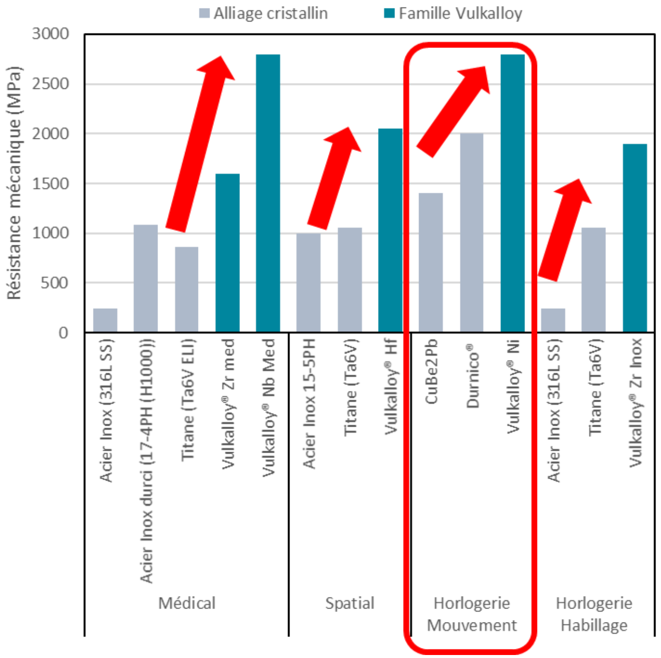


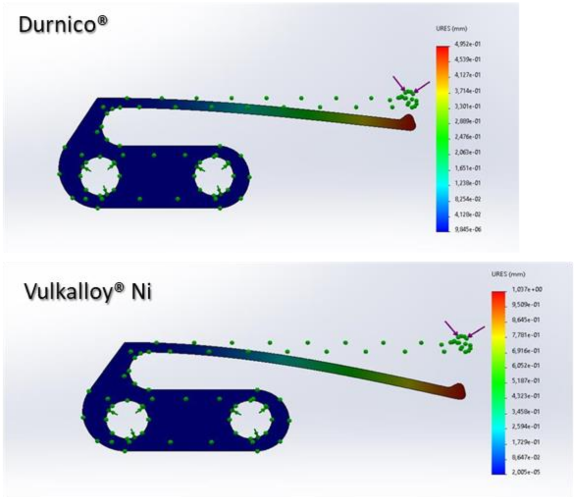
Mechanical and physical properties

- High elastic limit, High reversible deformation range
- High strength, High fatigue resistance
- High corrosion resistance
- High hardness, …

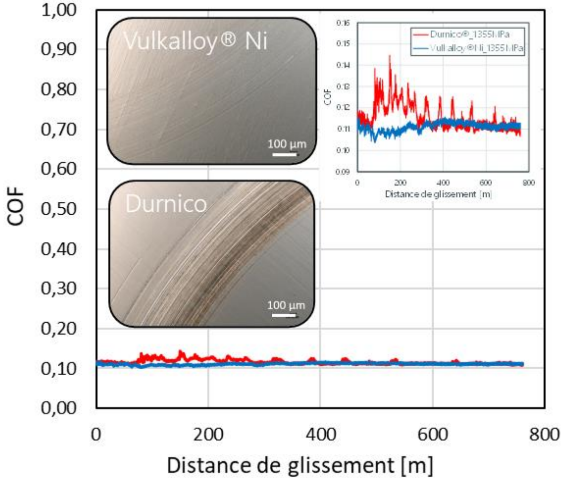


+ elongation of 1.8% !!





Maximum elastic deformation of microparts made from Vulkalloy® Ni and Durnico
→ Admissible deformation twice higher for Vulkalloy Ni



Friction and wear of Vulkalloy® Ni vs Durnico sliding agains CuBe @ 1350MPa
→ Very low wear and very stable friction, almost no wear for Vulkalloy ® Ni

BULK METALLIC GLASSES

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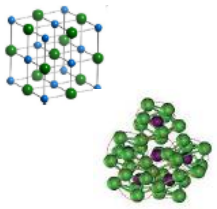


Mechanical and physical properties

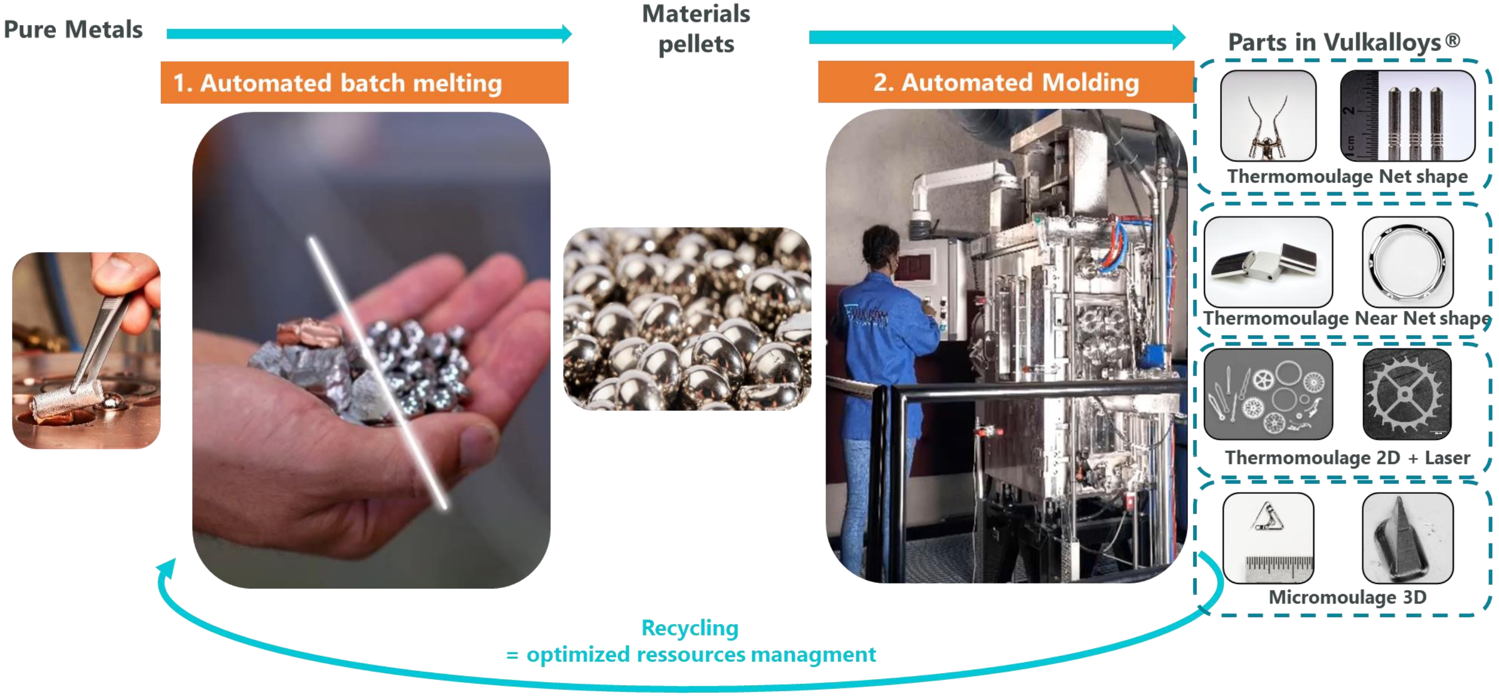
- High elastic limit, High reversible deformation range
- High strength, High fatigue resistance
- High corrosion resistance
- High hardness, …

Production line

4 patents

Unique know-how

Unique in-house designed machines



Extremely good molding properties

⇒ near netshape molding
⇒ Machining
⇒ Laser processing
⇒ …

BULK METALLIC GLASSES

LIMITED COMPONENT SIZE DEPENDING ON THE COMPONENTS

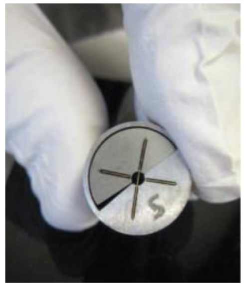
1. Micro-components
   - 0,2 à 10 mm3
   - Tolerances < 2µm / Ra < 0,1
2. Miniature-components
   - 10 à 250 mm3
   - Tolerances ± 0,015 mm / Ra < 0,35
3. Millimeter size components
   - 250 à 1000 mm3
   - Tolerances ± 0,02 mm / Ra < 0,35

OBJECTIVE OF THE STUDY

- **Explore the potential of the BMG in flexure and rolling/sliding micro/mini applications**

❑ **Flexural Pivot / Bearing**

stroke increase wrt endurance limit




❑ **Micro Gears**

Lifetime increase wrt tribology

Torque capability increase wrt yield strength

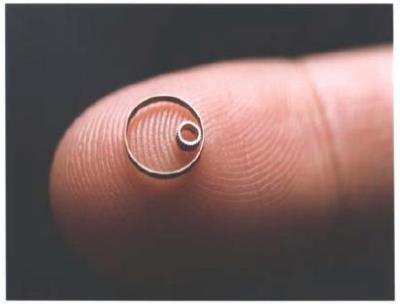


Fig. 5 Gear wheels in Nickel-Iron alloy

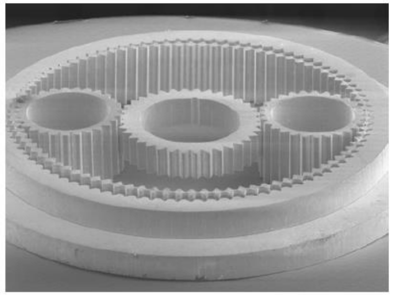


Fig. 6 Micro Harmonic Drive® gear component set

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MATERIAL CHOICE FOR THE STUDY

- Flexure materials, Harmonic drive (flexspline), gears
  - High to moderate E (160 GPa ideal for flexspline)
  - High strength and rupture strength
  - Good fatigue endurance
  - High tenacity

- Good corrosion résistance
- Low outgassing
- Low vaper pressure
- Low thermal expension
- Good wear resistance for tribological applications

		Vulkalloy Base Zr	Vulkalloy Base Cu	Vulkalloy Base Ni	TA6V	15-5PH H1025	440C
Dureté	(HRC)	42	48	**63**	41	35	59
Déformation élastique	(%)	2	2	**1,8**	0,7	0,5	1
Module d'Young	(GPa)	80	95	**150**	115	200	200
Limite d'élasticité	(MPa)	1660	1900	**2800**	860	1000	1900

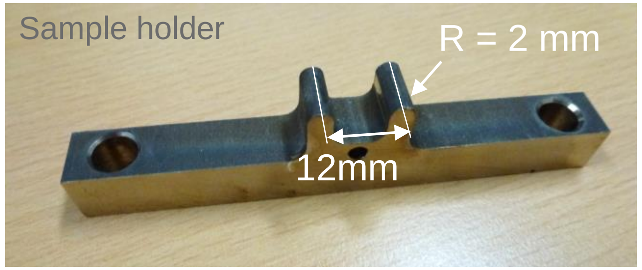
- BMGs meeting all requirements (in general) are Ni-based and Cu-Zr-based
  - Ni-based offers the best corrosion resistance than Cu-Zr
  - NI-based offer better corrosion resistance than 17-4 PH (acier utilisé aussi dans les engrenages *(Hampson 2015)*)
    - Ni-base equal 15-5PH
- Additionnal advantage of BMG: surface roughness

Vulkalloy Ni appears the best option

BULK METALLIC GLASSES

FATIGUE TESTS – QUASI STATIC 3 POINT BENDING

- Samples
  - Dimensions : 20*4,8*0,48 mm en AMA Ni1
  - From 2 batches
  - Polished to Ra < 0.2



- *Instron ELECTROPULS E10 000*
- *Load cell of 1 KN*

- 3 different tests
  - Quasi-static
    - 5 repetitions
    - Load @ 1mm/min
    - Until rupture
  - Whöler curves
    - 10e6 cycle
    - 30 Hz
    - R = 0.1
    - 13 tests
  - Fatigue endurance tests
    - Staircase method ISO 12107/2012
    - 10e7 Cycle
    - 30 Hz
    - R = 0.1
    - Step of 50 Mpa
    - 15 tests

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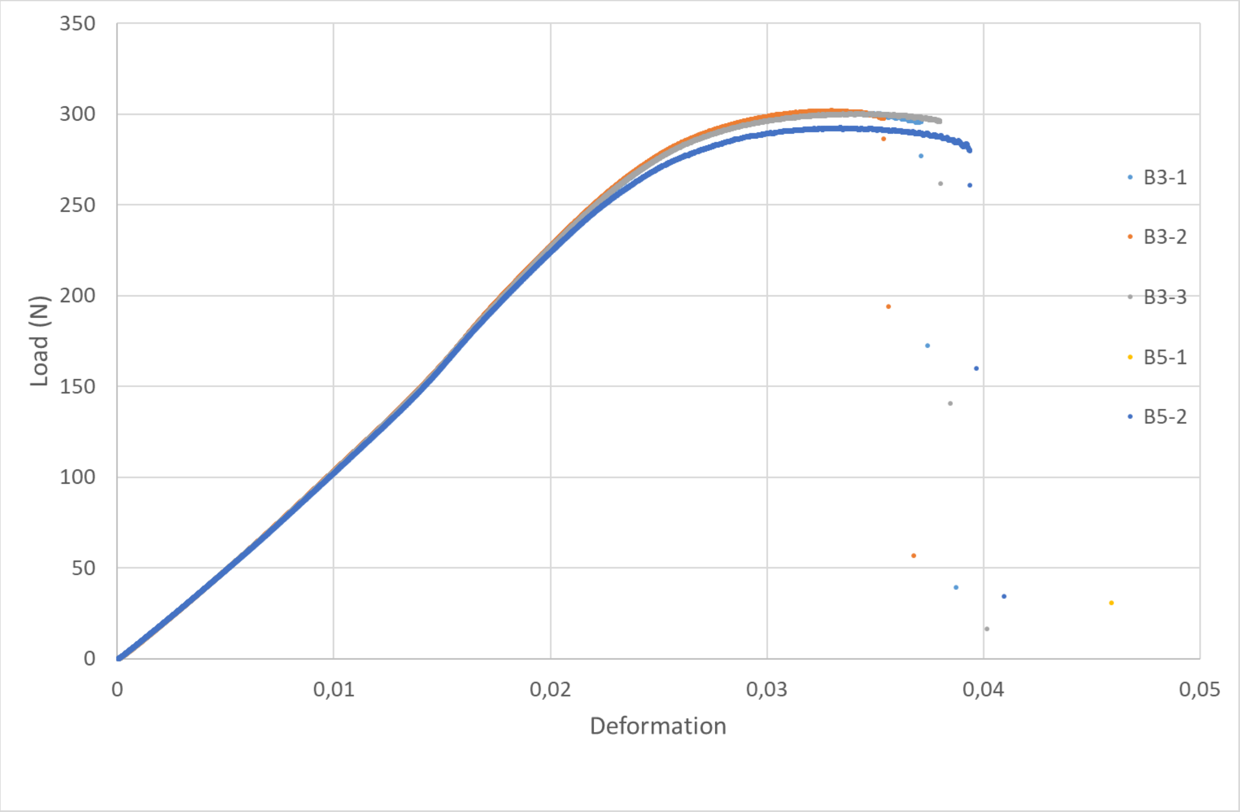
FATIGUE TESTS – QUASI STATIC 3 POINT BENDING

- ➢ Load vs deformation



- ➢ 2 mm deflection @ rupture !
  - ➢ Need to take it into account in the deformation calculation
- ➢ Highly reproducible

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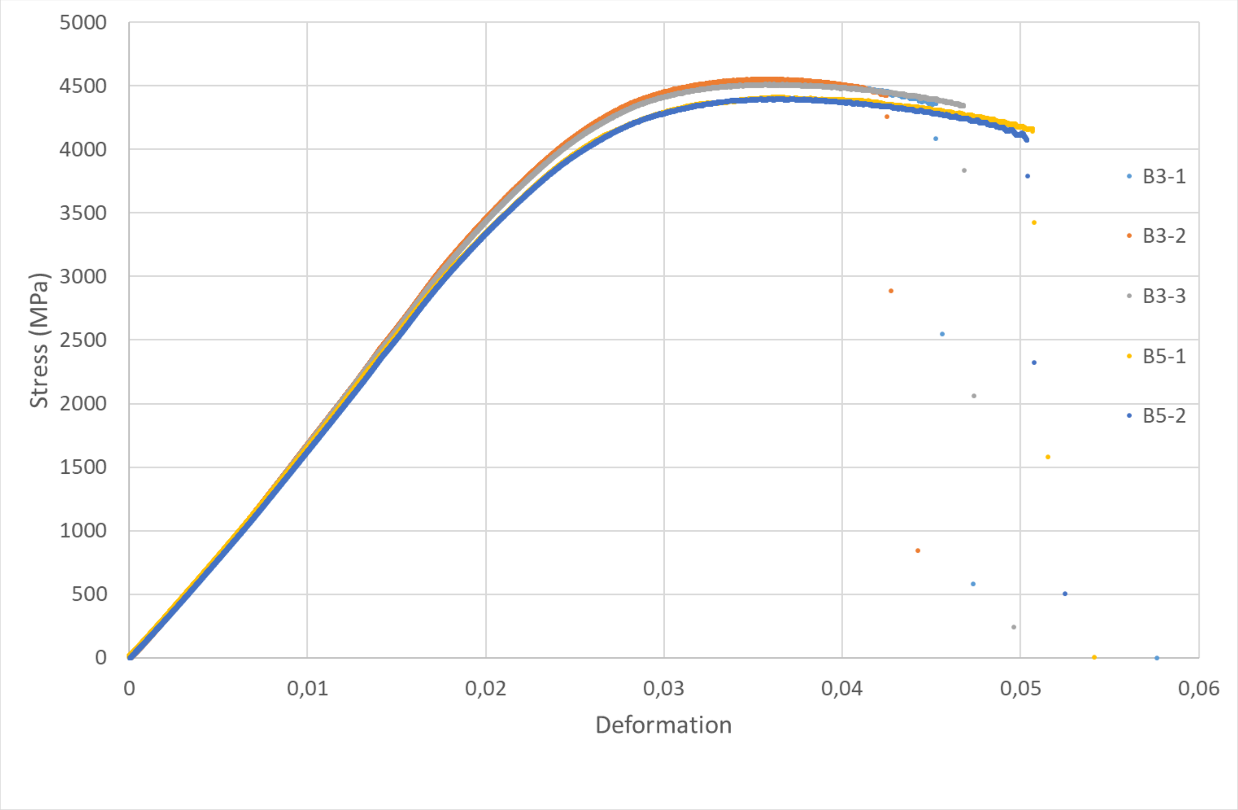
FATIGUE TESTS – QUASI STATIC 3 POINT BENDING

- Stress vs deformation => corrected data



- 2 mm deflection @ rupture !
  - Need to take it into account in the deformation calculation
- Highly reproducible
- Rupture due to local plasticization of the loading points
- Deformation at rupture not relevant due to traction and compression stresses over the sample thickness

	Re (MPa)	Rm (MPa)	Rupture Stress (MPa)
B3-1	2850	4560	4362
B3-2	2840	4557	4255
B3-3	2845	4555	4344
B5-1	2838	4402	4146
B5-2	2835	4408	4076
Moyenne	**2841,6**	**4496,4**	**4236,6**
Ecart-type	**5,31**	**74,67**	**110,99**

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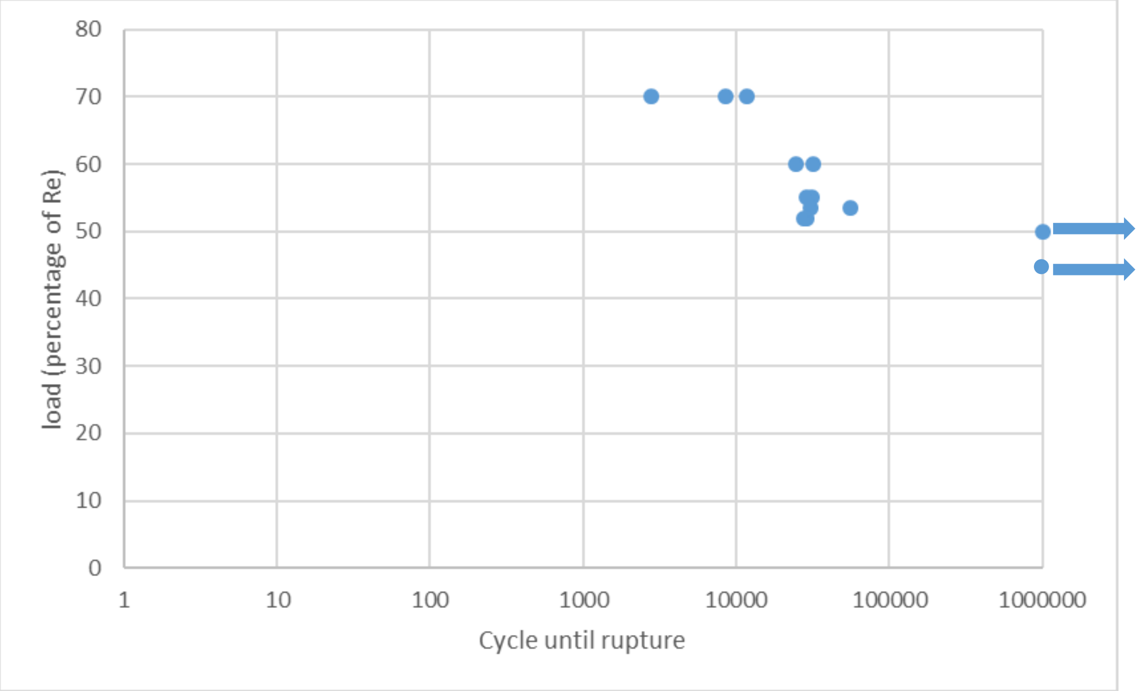
FATIGUE TESTS – 3 POINT BENDING – WÖHLER CURVE

- Load applied calculated based on each sample geometry
- Reminder :
  - 10^e6 cycle unless rupture ; 30 Hz ; R = 0.1



Percentage of elastic limit	Cycle to rupture	Batch N°
70	2 759	B5
70	8 561	B3
70	11 811	B5
50	1 000 000	B3
50	1 000 000	5
45	1 000 000	B3
60	24 652	B5
60	31 954	B3
55	31 153	B3
55	28 893	B5
52	29 079	B5
52	43 894	B5
52	27 432	B3

- **Binary response : pass or fail early (< ~50 000 cycles)**

BULK METALLIC GLASSES

FATIGUE TESTS – 3 POINT BENDING – STAIRCASE

- Load applied calculated based on each sample geometry
- Reminder :
  - 10e7 cycle unless rupture ; 30 Hz ; R = 0.1

O : sample passed
X : sample failled

	Test number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Batch number														
Stress (Mpa)	B5	B3	B3	B3	B3	B3	B5	B3	B3	B5	B3	B5	B3	B3	B5
1550			X				X								
1500		O		X		0		X		X					
1450	O				0				O		X		X		
1400												O		X	
1350															O
Cycle @ rupture			30 690	27 432			55 715	18 936		43 894	26 298		33 487	38 740	

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- **Binary response : pass or fail early (< ~50 000 cycles)**

BULK METALLIC GLASSES

FATIGUE TESTS – 3 POINT BENDING – STAIRCASE

- Load applied calculated based on each sample geometry
- Reminder :
  - 10e7 cycle unless rupture ; 30 Hz ; R = 0.1

With samples that failed the test

contraintes Mpa	15 éprouvettes 8 rompues			
	i	ni	i*ni	i²*ni
1550	4	0	0	0
1500	3	2	6	18
1450	2	3	6	12
1400	1	1	1	1
1350	0	1	0	0
Pas p (Mpa)	50			
Coeff N	7			
Coeff A	13			
Coeff B	31			
σ0 (Mpa)	1350			
Résistance en fatigue σD (Mpa)	**1468**			
Condition de validité écart-type	0,98			
Ecart-type s (Mpa)	**82**			

With samples that passed the test

contraintes Mpa	15 éprouvettes 7 non rompues			
	i	ni	i*ni	i²*ni
1550	4	2	8	32
1500	3	3	9	27
1450	2	2	4	8
1400	1	1	1	1
1350	0	0	0	0
Pas p (Mpa)	50			
Coeff N	8			
Coeff A	22			
Coeff B	68			
σ0 (Mpa)	1350			
Résistance en fatigue σD (Mpa)	**1463**			
Condition de validité écart-type	0,98			
Ecart-type s (Mpa)	**78**			

Endurance Limit (R=0.1, 50%) = 1460MPa

Standard Deviation : 5,6% (< typical 8% for standard alloys)

Endurance Limit with 99.9% reliability (R=0.1, 99,9%) = 1190MPa

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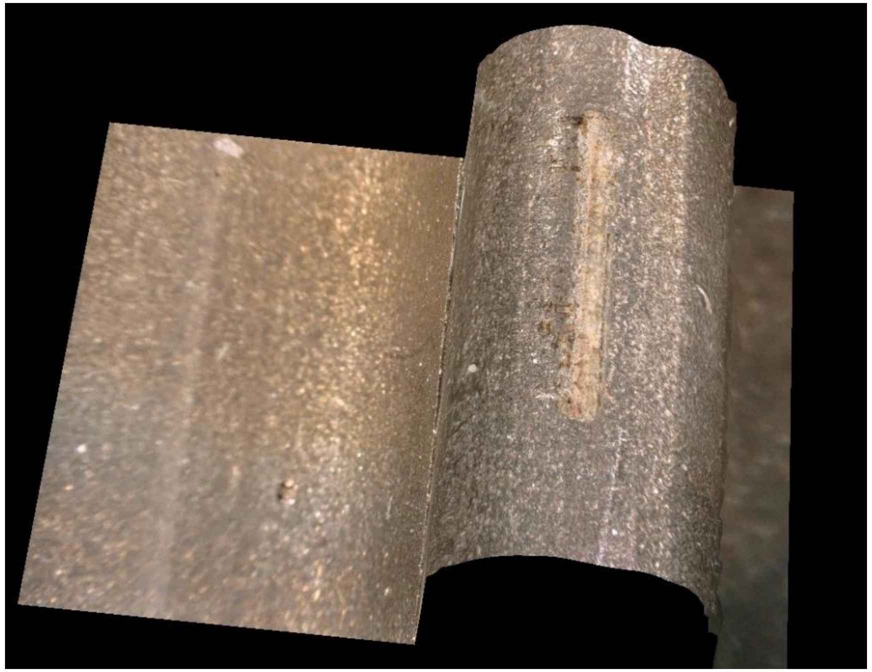
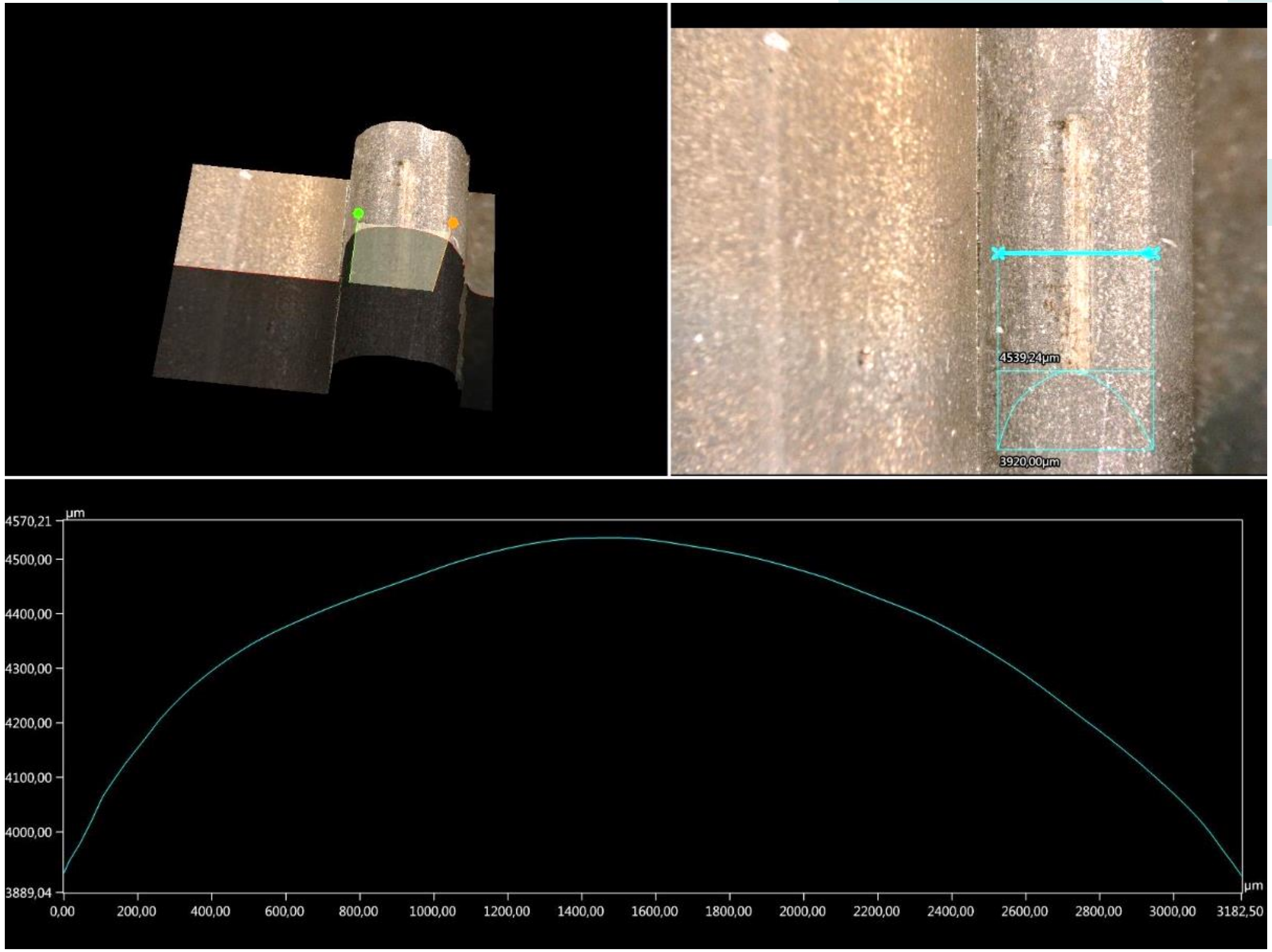
FATIGUE TESTS – 3 POINT BENDING

- Sample holder post test verification



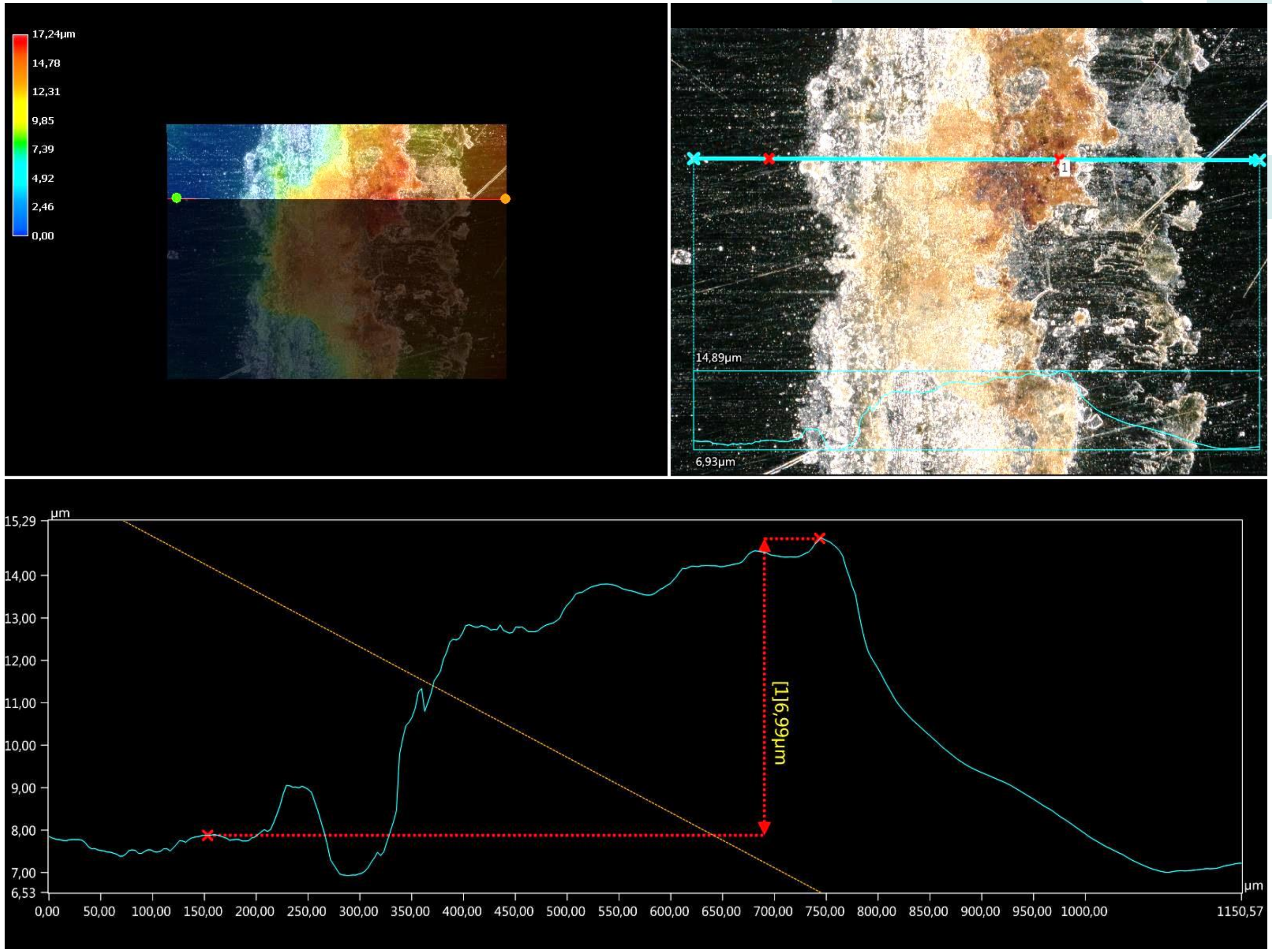


- Wear marks located at the contact points between BMG sample and sample holder
  - No significant damages detected => geometry not impacted

BULK METALLIC GLASSES

FATIGUE TESTS – 3 POINT BENDING

- ➢ Sample post test verification



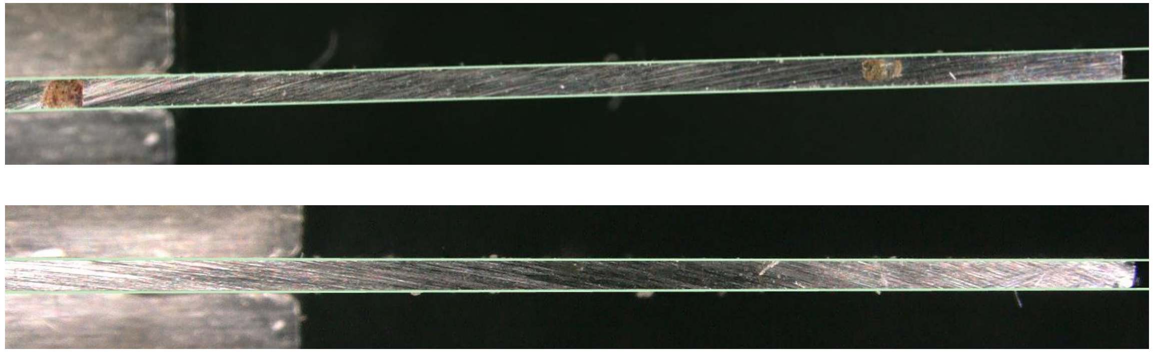
- ➢ Wear marks located at the contact points between BMG sample and sample holder
  - ➢ Transferred material from the holder

BULK METALLIC GLASSES

FATIGUE TESTS – 3 POINT BENDING

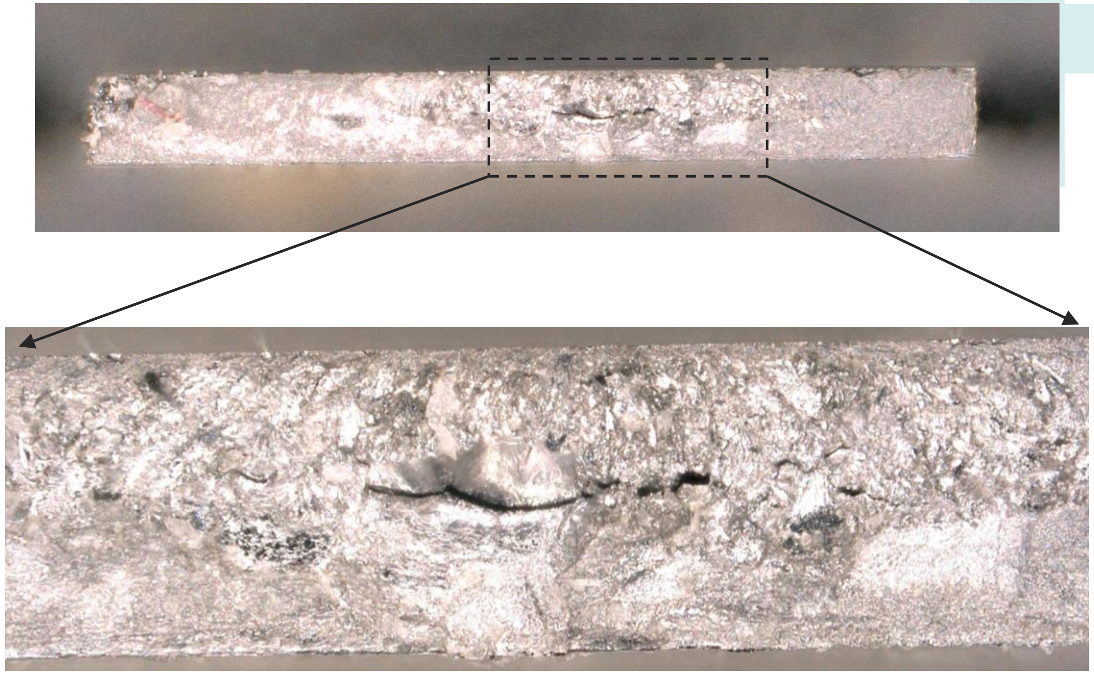
- Sample post test verification

Geometry of successful samples



- Samples that passed the endurance tests are not showing any deformation after test.

Rupture surface



- Cracks visible in the rupture section, mostly at the neutral fiber
- Normal features and morphologies of the section for a BMG sample

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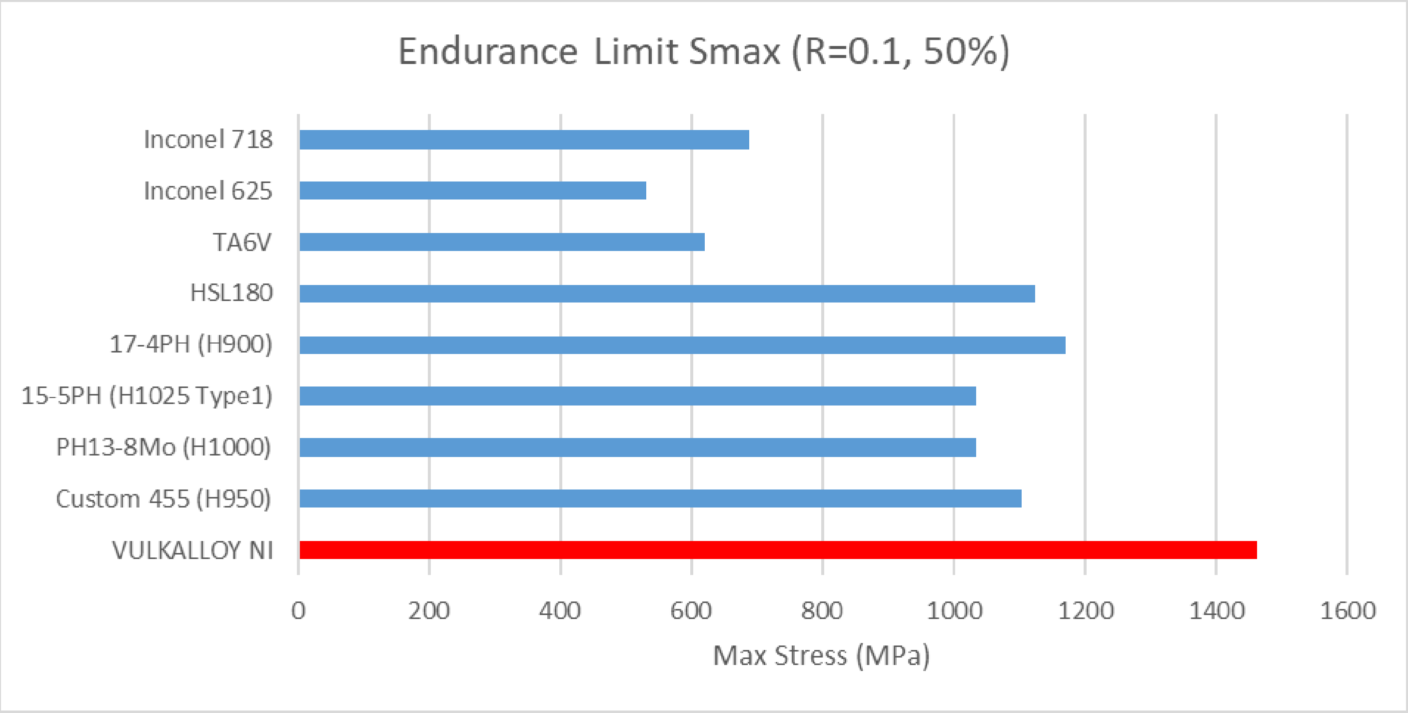
FATIGUE TESTS – RESULTS SYNTHESIS
+ COMPARISON WITH COMMON MATERIALS

Property	Unit	Vulkalloy Ni
Typical Thickness	mm	<1
Density	kg.mm3	8800
CTE	ppm/K	11
Hardness	HRC	63
Young Modulus	GPa	151
Yield Stress	MPa	2840
Endurance limit (R0.1, 50%)	MPa	1460
Endurance limit standard deviation	MPa	85



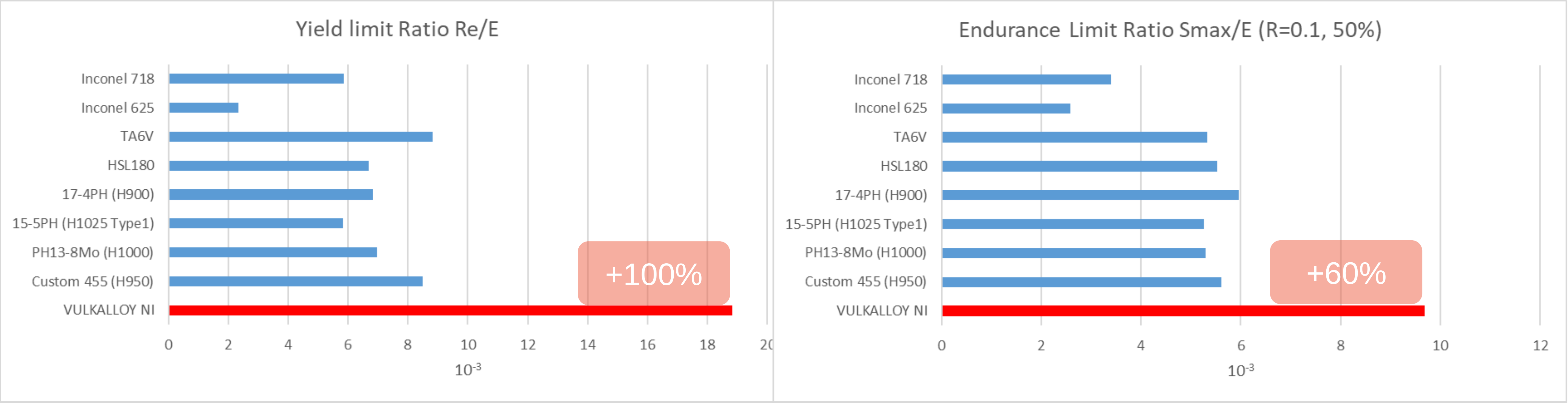
- Standard Deviation : 5,6% (< typical 8% for standard alloys)
- Endurance Limit with 99.9% reliability (R=0.1, 99,9%) = 1190MPa

Common Alloys Data Source : MMPDS

BULK METALLIC GLASSES

FATIGUE TESTS – COMPARISON WITH COMMON MATERIALS

Strain capability proportional to Stress to Modulus ratio



- ➢ **VulkalloyNi surpasses all the reference materials**
- ➢ **Extremely promising material for flexure applications**

BULK METALLIC GLASSES

FATIGUE TESTS – CONCLUSION

- Vulkalloy Ni surpasses all the reference materials
- Extremely promising material for flexure applications
  - Accept larger deformation ranges than crystalline material
  - No needs for specific design rules

Ready to be used

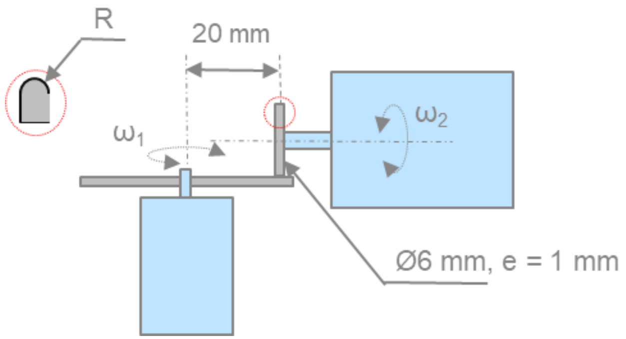
Call for application case

- For Harmonic Drive flexspline
  - Flexspline displacement is fixed => for a fixed loading, stress imposed will be lower if Young's modulus is lower
  - ISO geometry => Vulkalloy Ni will induce lower stress
    - Higher propency for low wear
- Industrial scale manufacturing process (plates, rode, finished and semifisnished parts)
  - Includes formulation, molding, machining, etc…

BULK METALLIC GLASSES

NEXT STEP : TRIBOLOGICAL TESTS

- Rolling with sliding study for HD and gear applications
- Main contact conditions
  - Vacuum: 5.10e-7 mbar, and Air 50%HR
  - Sliding to Roll Ratio (SRR) = 30%,
  - 1.2 GPa contact pressure
  - 3 types of contacts :
    - BMG / BMG
    - BMG / 15-5PH 1075
    - 15-5PH 1075 / 15-5PH 1075
  - 3 tests per contact types per environments



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THANKS FOR YOUR ATTENTION

Thanks to CNES for supporting the study

See you next time for the rolling with sliding test results…

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