



#### The magic of magnetic shape memory...

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FZU

• Intro & macrotwins

• Movie with examples

- Microtwins
- Nanotwins
- Summary





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### Structure as a $3\overline{2}$ stacking sequence





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# Structure as a $3\overline{2}$ stacking sequence







### Structure as a $3\overline{2}$ stacking sequence



Heczko, Oleg, et al.Acta Materialia 115 (2016): 250-258.



Straka, L., et al., Acta Materialia 132 (2017): 335-344. Straka, L., et al., Scientific Reports 8.1 (2018): 11943.

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L. STRAKA





### Structure as a $3\overline{2}$ stacking sequence





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# Structure as a $3\overline{2}$ stacking sequence



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# a/b twins as a $3\overline{2}$ stacking sequence inversion

a/b twin boundary = stacking sequence inversion ...323232 | 232323...





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a/b twin boundary = stacking sequence inversion ...323232 | 232323...







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Yu U. Wang, Phys. Rev. B 74 (2006), 104109 Yu U. Wang, Phys. Rev. B, 76 (2007), Article 024108





a/b twin boundary = stacking sequence inversion ...323232 | 232323...



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a/b twin boundary = stacking sequence inversion  $...3\overline{2}3\overline{2}3\overline{2}|2\overline{3}2\overline{3}2\overline{3}...$ 



a/b twin boundary = stacking sequence inversion ...323232 | 232323...



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a/b twin boundary = stacking sequence inversion ...323232 | 232323...

Nanotwins - adaptive diffraction condition:

m < 2/sH

where s = 0.0045 is twinning shear and H = 4 is reciprocal space coordinate

=>

size of a/b twin

m < 20 nm (100 atomic planes)



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# a/b **nano**twins as a $3\overline{2}$ stacking sequence inversion

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# a/b **nano**twins as a $3\overline{2}$ stacking sequence inversion

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#### Modulation



Heczko, Oleg, et al.Acta Materialia 115 (2016): 250-258.







#### Modulation



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### Modulation – study by high-resolution q-scan



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### Modulation – study by high-resolution q-scan



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Straka L. et al., submitted, http://dx.doi.org/10.2139/ssrn.4771525 Heczko, Oleg, et al.Acta Materialia 115 (2016): 250-258.

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Atomic plane nr.

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Czech Academy of Sciences Ø Institute of Physics of the Czech Academy of Sciences FZU MAGNETIC MEASUREMENTS AND MATERIALS q<sub>c</sub>' Aperiodicity – study by high-resolution q-scan commensurate (b) (2<sup>2</sup>0) (400) **300** 260 Log. intensity (a.u.) q<sub>ic</sub>' 180 incommensurate 140 100 2 2.4 2.8 3.2 3.6 4 h, k-4 (-) **q**=(q,q,0) q'=2/q

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Straka L. et al., submitted, http://dx.doi.org/10.2139/ssrn.4771525

The magic of magnetic shape memory alloys and crystal structure perspective

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### Aperiodicity – study by high-resolution q-scan

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**q**=(q,q,0) q'=2/q

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Straka L. et al., in preparation





#### Aperiodicity results in a/b nanotwinning (!!!)



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#### Aperiodicity results in a/b nanotwinning (!!!)



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#### Aperiodicity results in a/b nanotwinning (!!!)



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(a) q = 0.400, q' = 5.00 (10M commensurate)

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#### Distinct identified nanotwins/structures



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Distinct identified nanotwins/structures as low energy/low temperature states

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Hypothesis yet to be tested: q converges to one of the nanotwinned states

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			N	q'	q	Domain size	Domain size	Marking
140-	0.430	•• <del>-</del> •	-	(planes)	(-)	(planes)	(nm)	-
	0.425 -	▼ ● ►	1	4.000	0.5000	4	0.8	40
	0.420 -	▲ • •	2	4.500	0.4444	9	1.9	180*
240 -	-0-415-	•••	3	4.667	0.4286	14	2.9	140
	0.415	• • •	4	4.750	0.4211	38	8.0	38O*
340 -	0.410	•··	5	4.800	0.4167	24	5.0	240
(-) b	0.405 -	•	6	4.833	0.4138	58	12.2	58O*
	0.400 -		7	4.857	0.4118	34	7.1	340
	0.400	▶ Righi 2007 ◆ Veřtát 2022 ▶ ▼ ▼	8	4.875	0.4103	78	16.4	780*
	0.395 -	Righi 2010 A Fukuda 2009	9	4.889	0.4091	44	9.2	44O
	0.390 -	Cakir 2015 Variager 2014	10	4.900	0.4082	98	20.6	98O*
	0.385 -	Veřtát 2021	11	4.909	0.4074	54	11.3	54O
	0.200		12	4.917	0.4068	118	24.8	118O*
	+ 086.0 0	50 100 150 200 250 300 350	00	5.000	0.4000	00	00	10M comm.**
	0	Temperature (K)	* Double cell size to comply with the $L2_1$ order.					
			** also marked as 5M when neglecting ordering.					

Straka L. et al., in preparation







#### Summary IV

#### Aperiodic crystal Anharmonic modulation

Wave modulation perspective vs nanotwinning perspective:

- not exclusive concepts but complementary/intertwinned concepts in Ni-Mn-Ga
- nanotwinning is a result of crystal aperiodicity
- Low temperature states are nanotwinned
- Nanotwinning ON/OFF (at r.t.)







#### Summary

#### Magnetic shape memory (Ni-Mn-Ga)

- very interesting at all scales
- magnetism important but (micro)structure critical for MSM functionality

#### - a great platform for

- magnetoelastic and magnetomechanical effects (up to 12% deformation in mag. field)
- martensite crystallography (deeply hierarchical martensite)
- nanotwinning and aperiodic crystal concepts (nanotwins on/of, aperiodicity on/offf)
- major **future** tasks: alternatives & applications















