High precision measurements of elastic anisotropy in metals

Bevis Hutchinson, Mikael Malmström, Anton Jansson, Peter Lundin

Origins of anisotropy

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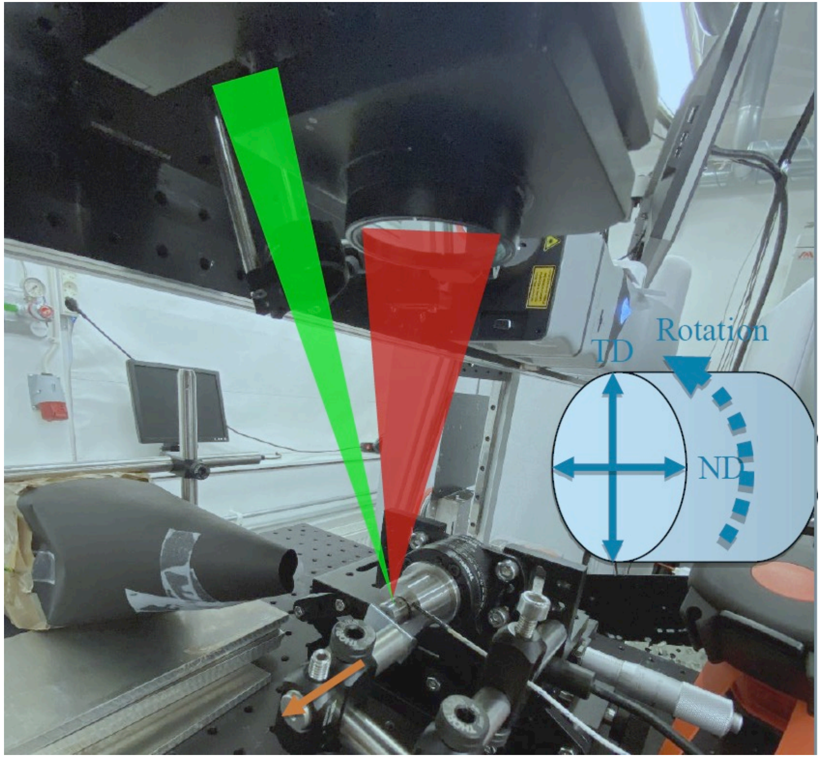
- All (single) crystals are elastically anisotropic so wave velocities inside them vary with direction
- In a random polycrystal these effects would cancel out leading to isotropy and invariant wave velocities
- However, solid polycrystals almost always contain preferred orientation (texture) so some of the crystal property is inherited by the material and wave velocites then vary with direction. Potentially, this gives us a possibility to characterise the texture from LUS measurements
- The magnitude of observed values depends on the texture strength and the intrinsic crystalline behaviour. Sometimes the variation is quite small so high precision is necessary in the measurements

Practical measurement of anisotropy

Since anisotropy means different values in different directions it is evident that it cannot be quantified with a single measurement. Various approaches have been suggested:

1. Rotating the material with respect to the instrument (Kitagawa 1981, Ledbetter et al. 1998, Thompson et al.1989, Tägtström et al 1992, Spalthoff et al. 1993, Hiwatshi et al. 1994, Anderson et al. 1996, Artymowicz et al. 2002, Lèveque et al. 2011, Dijuster et al. 2018)
2. Material static while changing the wave path using a masked axicon lens or galvano-mirror optics (Lévesque et al. 2011, Malmström et al. this conference)
3. Combining different wave types with the same direction of propagation such as S_0+S_{H0} or S_0+S_{H0}+P or P+S waves (Thompson et al. 1989, Kawashima 1990, Kawashima et al. 1993, Moreau et al. 1999)
4. Successive P-wave arrivals having the same points for laser generation and detection but different path directions (Bate et al. 2017)

Precision measurement of anisotropy



Usually the greatest source of error in LUS measurement comes from distance between the generation and detection lasers

Circular cylinder manufactured by turning with a lathe gives equal path lengths for all directions when the specimen is rotated

Strong P-wave reflections provide accurate determination of passage time

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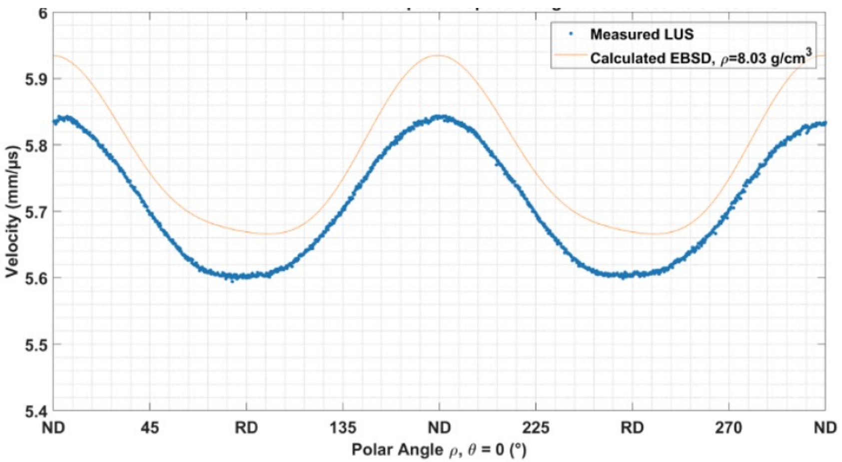
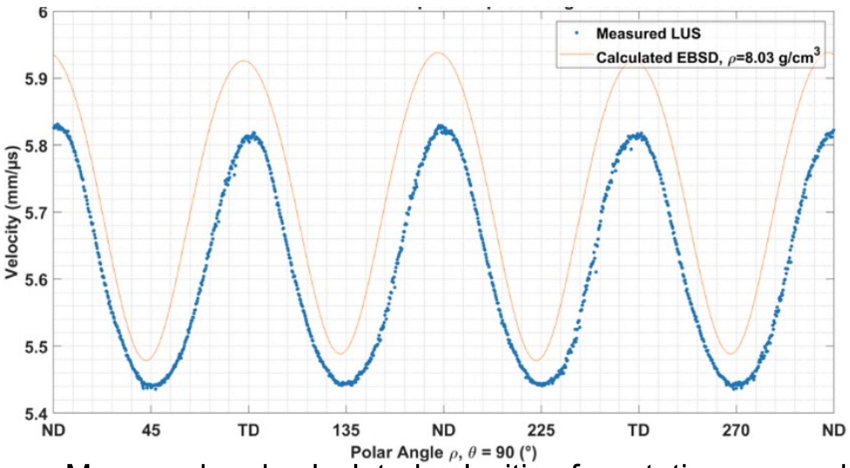
Application to 67% laboratory rolled 316 stainless steel plate



Measured and calculated velocities for rotations around the transverse direction TD



Measured and calculated velocities for rotations around the rolling direction RD

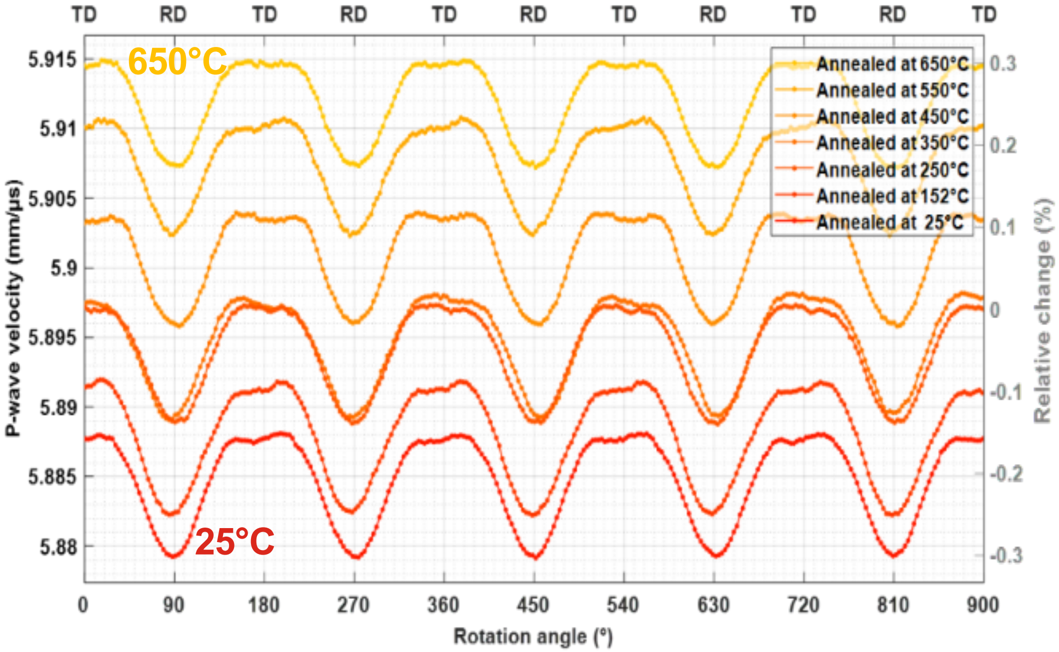
Calculated values are based on textures determined from EBSD measurements together with values of density and crystal coefficients (c_{11}, c_{12}, c_{44}) from the literature

The polycrystal model uses a Hill approximation. This may be the source of the consistent dfference between the absolute values of the curves.

Application to martensite

- Fundamental data about elasticity in martensite is lacking due to the impossibility of preparing single crystals
- There is also dispute about the true crystallography of low carbon ’lath’ martensite- whether tetragonal or cubic -so calculations of all types are unreliable.
- Polycrystalline measurements could give indications but the texture is always very weak so high precision is necessary
- After tempering at increasing temperatures the structure changes progressively to ordinary bcc ferrite

Measurements on martensite



7mm 0.3%C steel hot rolled and directly quenched plate
Samples tempered for 1 hour at indicated temperatures

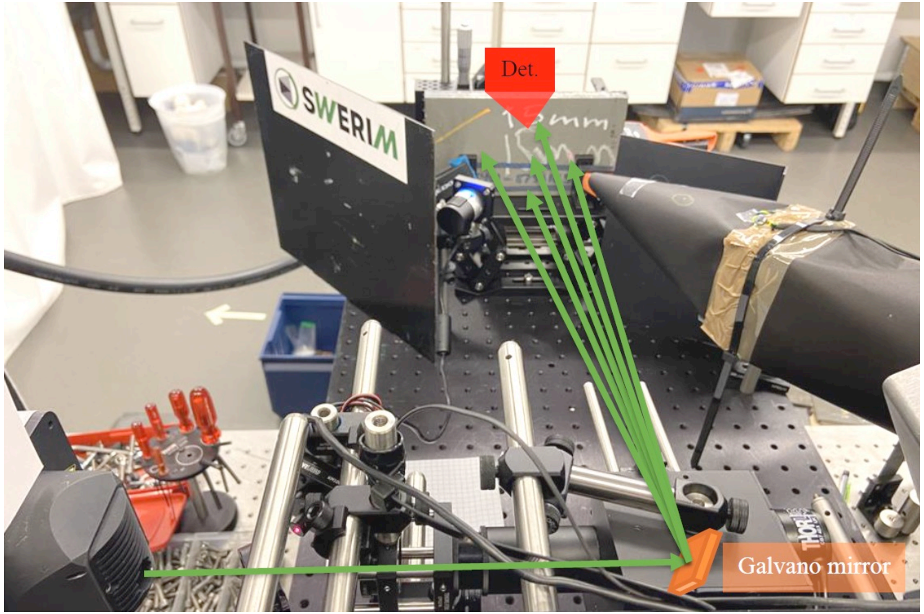
Measurements made at the plate centre in the RD-TD plane (specimen rotation around ND)

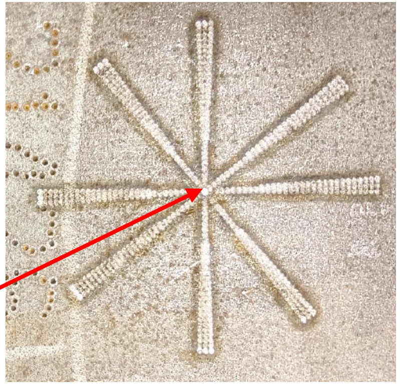
High reproducibility on repeated measurements

Low level of anisotropy – Maximum variation with angle only 0.12% but with precision of ~0.01%

The stiffness and wave velocity increases with tempering (~0.5%) but the anisotropy is almost identical for all structures from fresh martensite to bcc ferrite

Measurements using the galvano-mirror

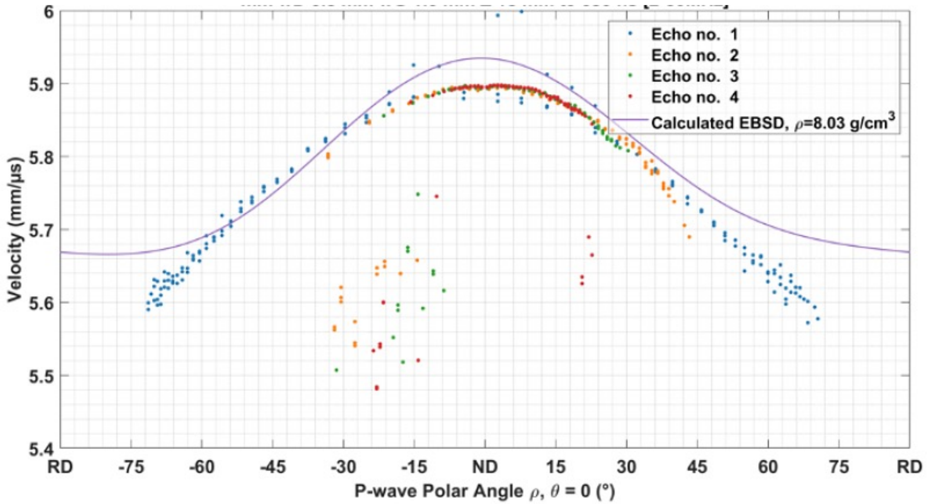




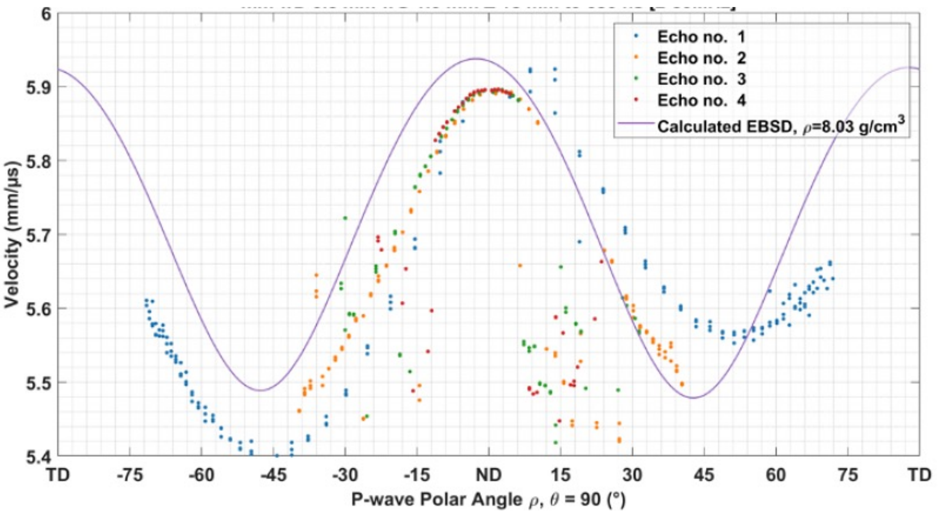
Generating laser is steered with the galvano-mirror while the detection laser is fixed in the central position

Burn patterns from the generating laser

Application to 67% laboratory rolled 316 stainless steel plate



Variation in velocity for directions in the ND-RD plane



Variation in velocity for directions in the ND-TD plane

Also here, density and crystal coefficients are obtained from the literature and a Hill approximation is used for calculating polycrystalline elasticity. Texture data are from EBSD measurements

For geometrical reasons it is not possible to measure signals at high angles to the plate normal direction

Example of ODF texture coefficients C_l^{mn} for cold rolled steel (typically 179 different coefficients)

i	L	Mu	Nu	Re
1	0	1	1	1.000
2	4	1	1	-0.372
3	4	1	2	-0.594
4	4	1	3	-0.980
	6	1	1	-2.932
6	6	1	2	2.887
7	6	1	3	-0.685
8	6	1	4	-0.610
9	8	1	1	0.287
10	8	1	2	-0.090
11	8	1	3	0.555
12	8	1	4	0.548
13	8	1	5	-0.594
14	9	1	2	0.162
15	9	1	3	0.460
16	9	1	4	-0.581
17	9	1	5	-0.381
18	10	1	1	0.356
19	10	1	2	-0.191
20	10	1	3	0.308
21	10	1	4	-0.647
22	10	1	5	0.640
23	10	1	6	0.784
24	12	1	1	0.057
25	12	1	2	-0.090
26	12	1	3	-0.047
27	12	1	4	-0.273
28	12	1	5	0.187
29	12	1	6	-0.940

These are the only ones that actually affect the elastic properties

30	12 0.000	1	7	1.018
31	12 0.000	2	1	1.806
32	12 0.000	2	2	-2.110
33	12 0.000	2	3	1.046
34	12 0.000	2	4	-0.060
35	12 0.000	2	5	-0.563
36	12 0.000	2	6	0.412
37	12 0.000	2	7	-0.610
38	13 0.000	1	2	-0.067
39	13 0.000	1	3	-0.113
40	13 0.000	1	4	-0.189
41	13 0.000	1	5	0.297
42	13 0.000	1	6	0.144
43	13 0.000	1	7	-0.062
44	14 0.000	1	1	-0.312
45	14 0.000	1	2	0.327

etc

-0.152

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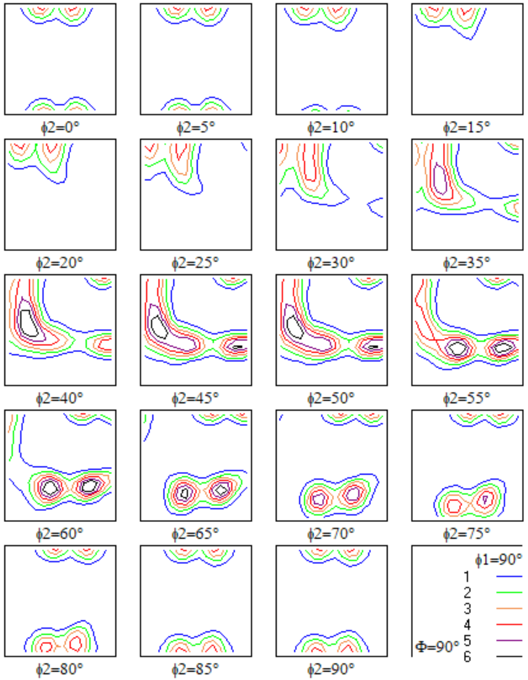
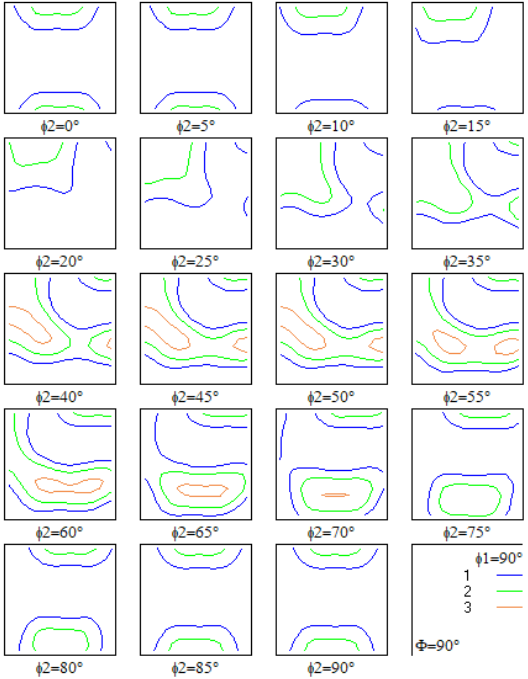
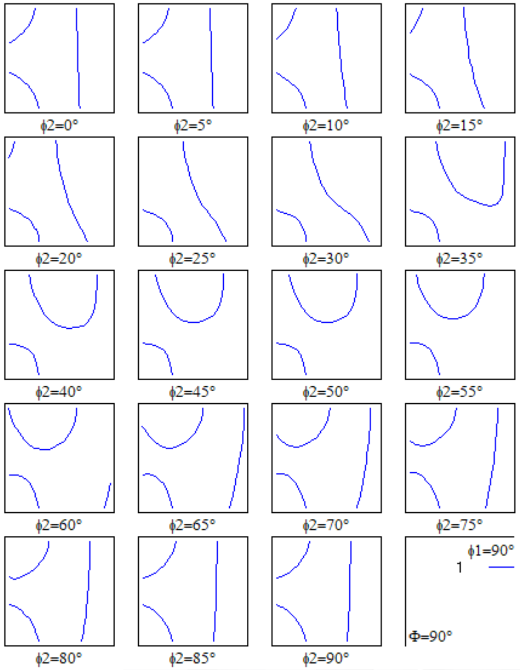
Plotting the same ODF with different expansions



ℓ_{max} =22 normal limit



ℓ_{max} = 8 smoothened



ℓ_{max} = 4 the best we can get with US measurements

Conclusions

- These instrumental developments open the way to very accurate measurements of elastic anisotropy in the laboratory
- There is good agreement between wave velocity values from LUS and calculations based on measured textures in the same material
- Nevertheless, textures derived from wave velocity measurements can only be approximate
- Using the galvano-mirror method, anisotropy and texture can be quantified reliably under industrial production conditions
- Elastic stiffness of martensite is somewhat lower than in standard bcc ferritic steel but the crystalline anisotropy in these appears to be closely similar

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