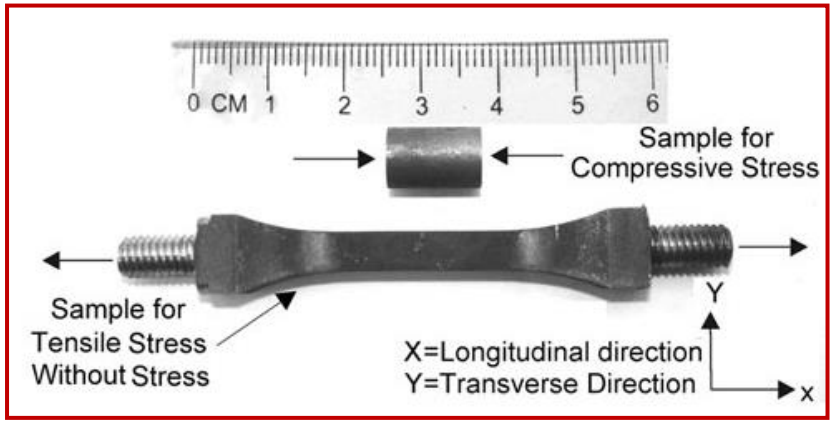
The dilatometric and microstructural response of variant selection during α' transformation

Ankita Mangal[a], Pinaki Biswas[a],
Shiv Brat Singh[b] and Saurabh Kundu[a]

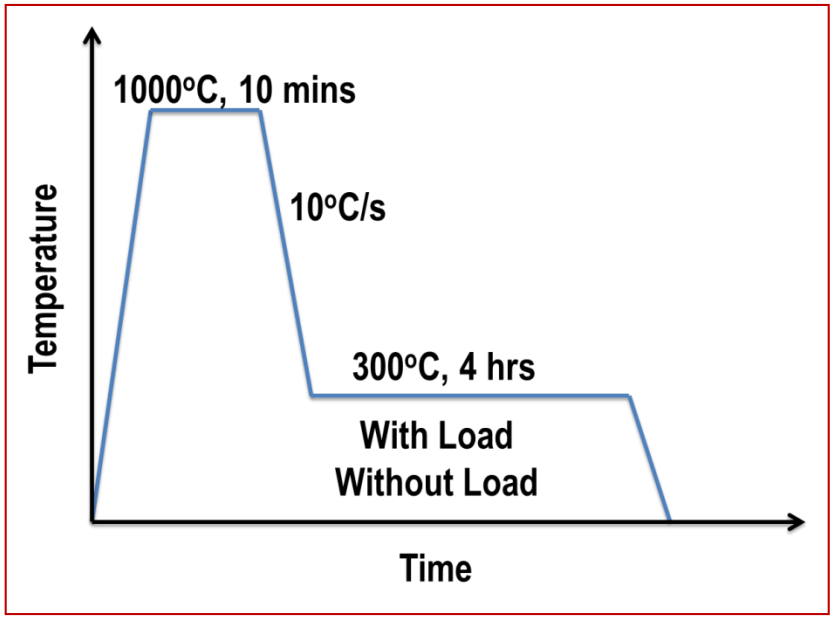
a: *Tata Steel, India* ***b:*** *IIT Kharagpur*

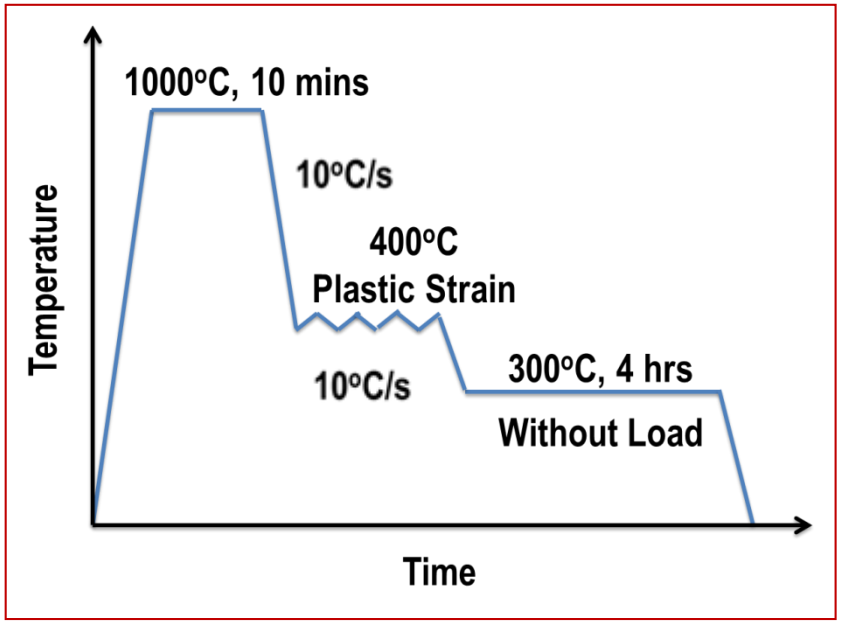
Acknowledgements:
Vijayalakshmi Singh
Itishree Mohanty
Shaumik Lenka

Experimental detail



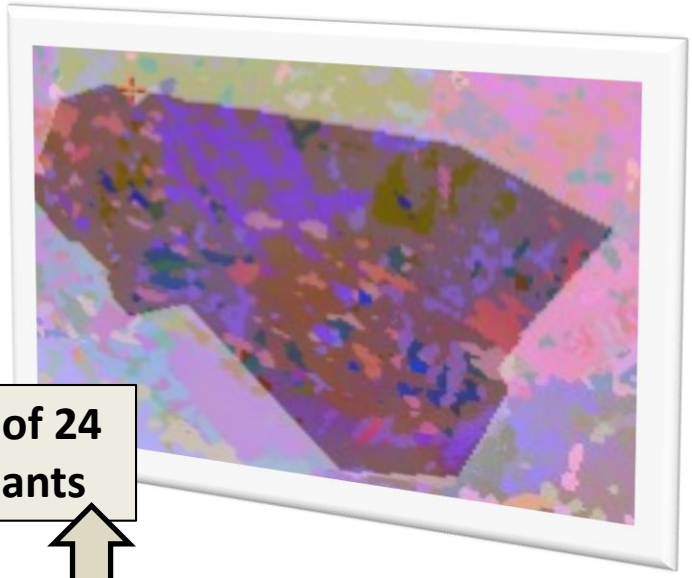
Fe-0.79C-1.56Si-1.98Mn-1.01Al
1.1Cr-1.0Co-0.24Mo





Determination of ideal bainite orientation in a γ grain

	ϕ1	ϕ	ϕ2
1	159.1	169.7	233.2
2	282.5	15.4	94.0
3	335.2	24.3	223.9
4	340.0	113.5	234.3
5	158.1	80.4	219.7
6	125.7	153.1	21.2
7	145.9	65.3	43.3
8	325.1	100.7	49.8
9	156.7	156.3	320.1
10	341.7	10.9	306.9
11	102.7	163.8	88.8
12	160.5	67.2	308.2
13	338.8	100.1	323.1
14	304.0	26.6	163.0
15	52.4	80.2	64.7
16	325.3	114.2	139.1
17	144.6	78.7	132.9
18	232.0	99.0	117.9
19	244.9	103.6	209.7
20	236.7	86.4	28.9
21	55.9	93.2	153.7
22	69.0	89.8	243.2
23	65.6	76.7	332.8
24	249.4	90.9	299.4



Orientation of 24 bainite variants

$$g_s^{\alpha(i)} = g_\gamma^{\alpha(i)} \cdot g_s^{\gamma}$$

Orientation Relationship : Calculated using PTMC

Orientation of γ grain Experimentally obtained

Identification of bainite variants

Model Prediction

g_B

	ϕ1	ϕ	ϕ2
1	159.1	169.7	233.2
2	282.5	15.4	94.0
3	335.2	24.3	223.9
4	340.0	113.5	234.3
5	158.1	80.4	219.7
6	125.7	153.1	21.2
7	145.9	65.3	43.3
8	325.1	100.7	49.8
9	156.7	156.3	320.1
10	341.7	10.9	306.9
11	102.7	163.8	88.8
12	160.5	67.2	308.2
13	338.8	100.1	323.1
14	304.0	26.6	163.0
15	52.4	80.2	64.7
16	325.3	114.2	139.1
17	144.6	78.7	132.9
18	232.0	99.0	117.9
19	244.9	103.6	209.7
20	236.7	86.4	28.9
21	55.9	93.2	153.7
22	69.0	89.8	243.2
23	65.6	76.7	332.8
24	249.4	90.9	299.4

Misorientation Δg_{AB}

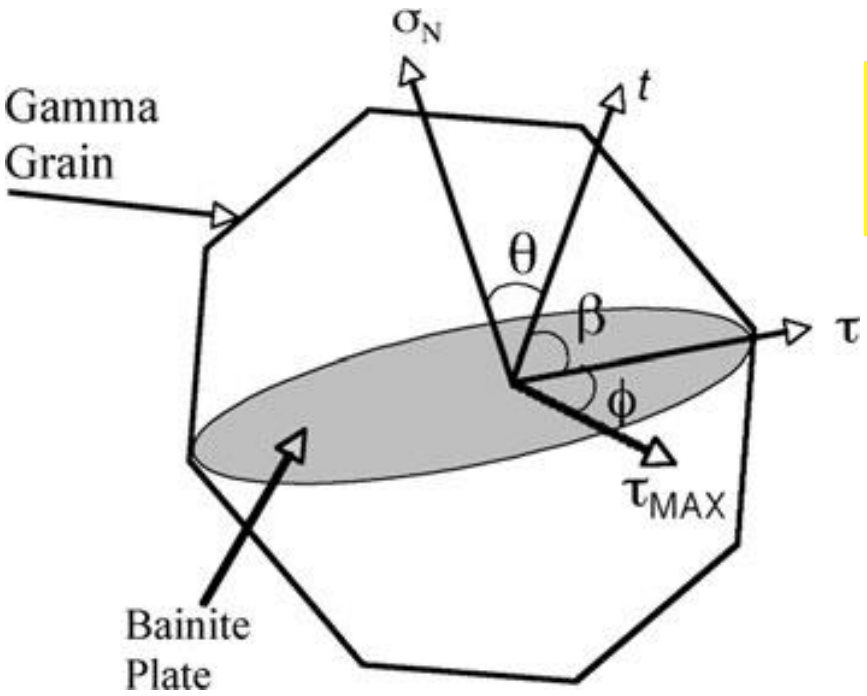
23.1
17.9
14.5
56.9
52.2
6.9
51.3
57.8
16.1
22.5
17.8
54.6
53.2
5.3
49.4
53.2
57.7
46.9
54.0
43.8
45.1
55.2
55.4
54.5

g_A **From EBSD map**

ϕ1	ϕ	ϕ2
34.8	77.9	207.8

$$\Delta g_{AB} = g_B \cdot g_A^{-1}$$

Interaction Energy

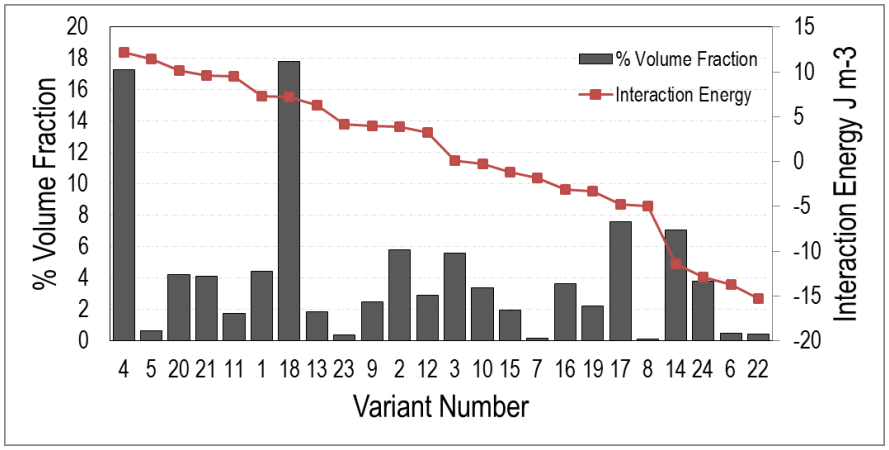


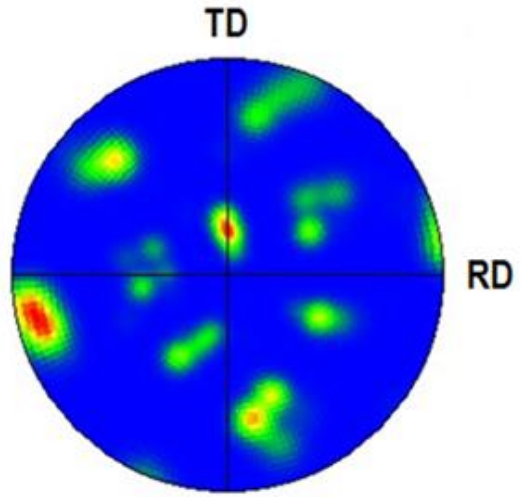
$$\sigma_N = |t|\cos\{\theta\}$$
$$\tau = |t|\cos\{\beta\}\cos\{\varphi\}$$

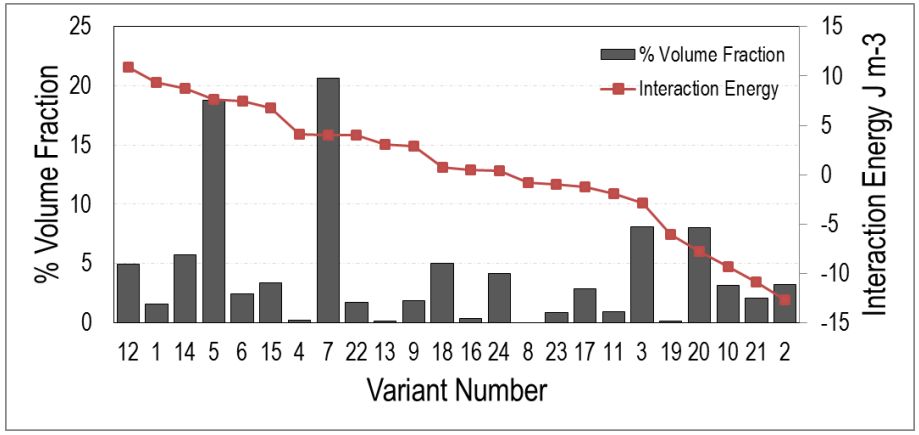
$$U = \sigma_N \delta + \tau . s$$

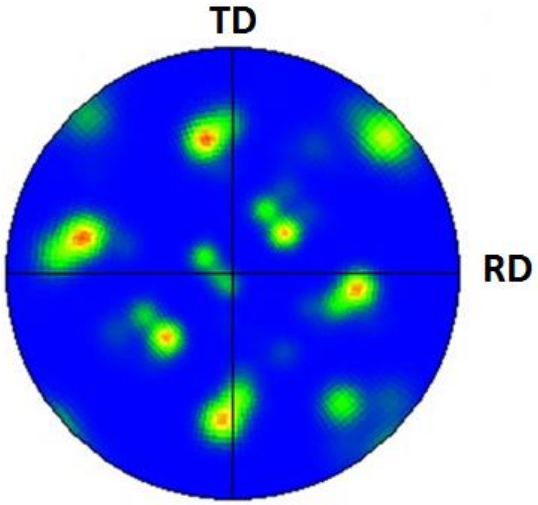
Kundu, Hase and Bhadeshia : PRSA, (2007), 463, 2309

Variant selection under tensile stress

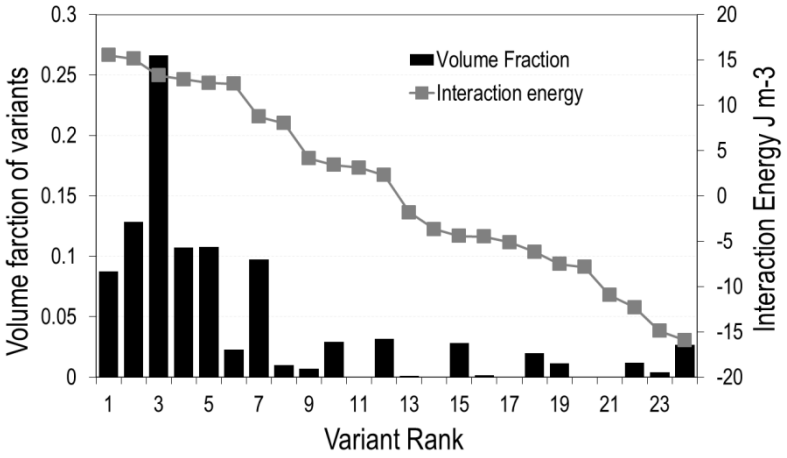




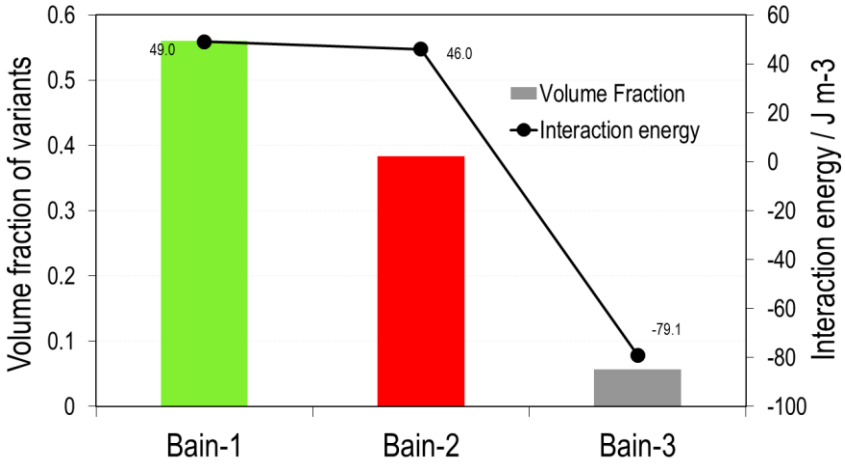




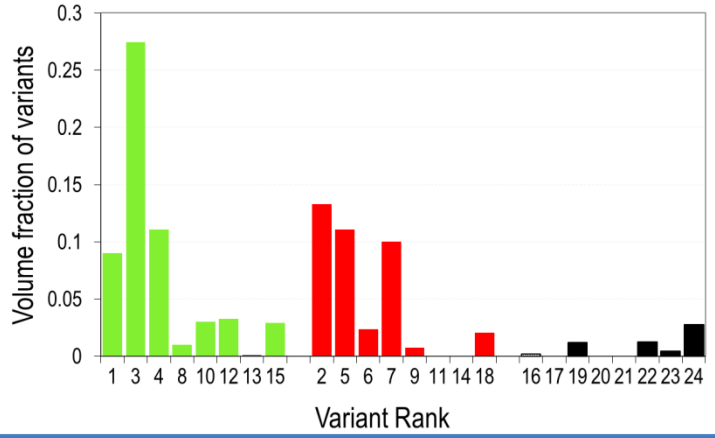
Prediction of Variant selection under tensile stress



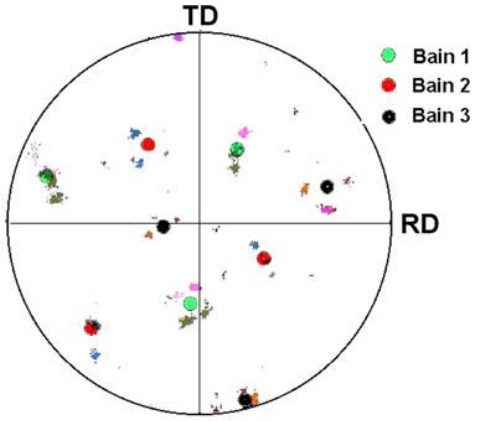
Vol. fraction and interaction energy of 24 variants



Vol. fraction and interaction energy of Bain Zones



Interaction energy of various Bain Zones



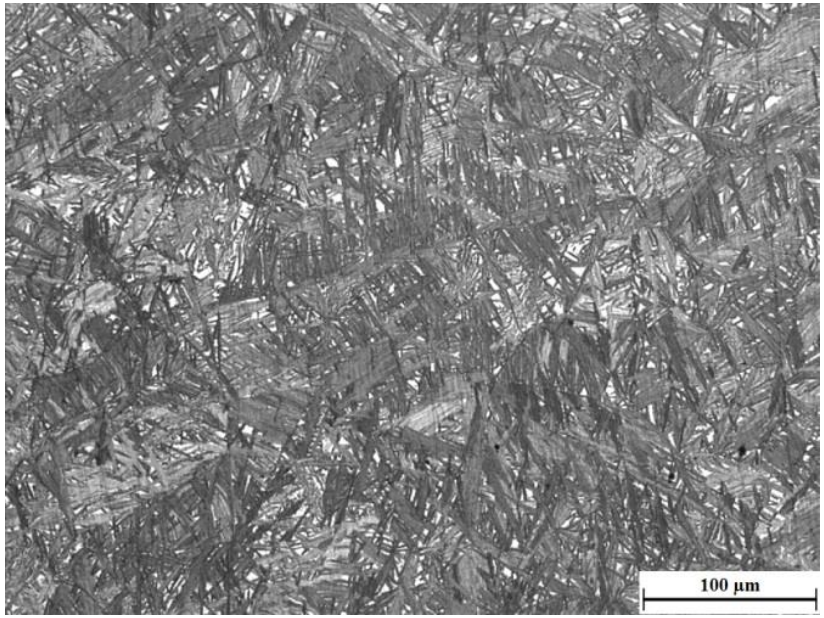
Description of Bain Zones

Kundu, Verma and Sharma: Met. Trans. A, (2012), 43A, 2552

Points to be noted so far

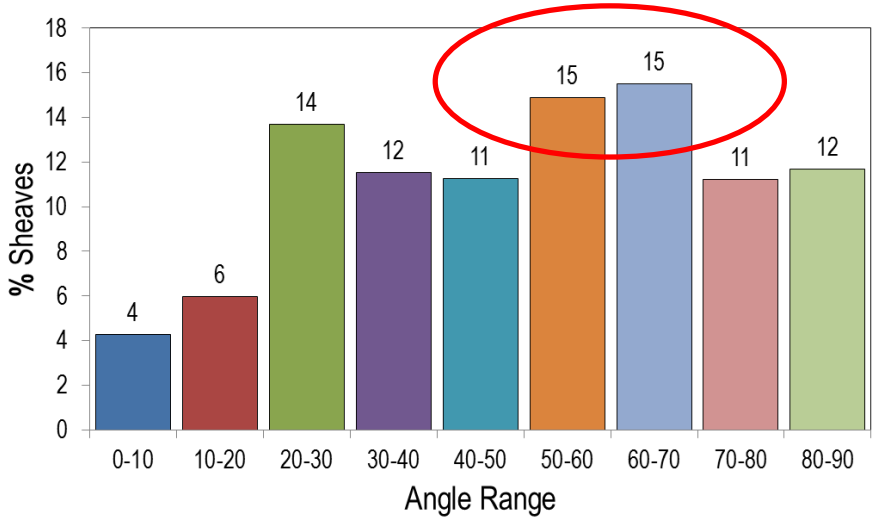
- Variant selection under stressed austenite is not strong.
- Variant selection under stress depends weakly on interaction energy of each variant.
- A better prediction of variant selection is obtained by considering cumulative interaction energy of all variants in a Bain Zone.
- It has been observed that volume fraction of variants in at least two of the three Bain zones are considerable.
- Variants within one Bain Zone have less misorientation between them which results in less hard impingement.

Orientation of sheaves under tensile stress



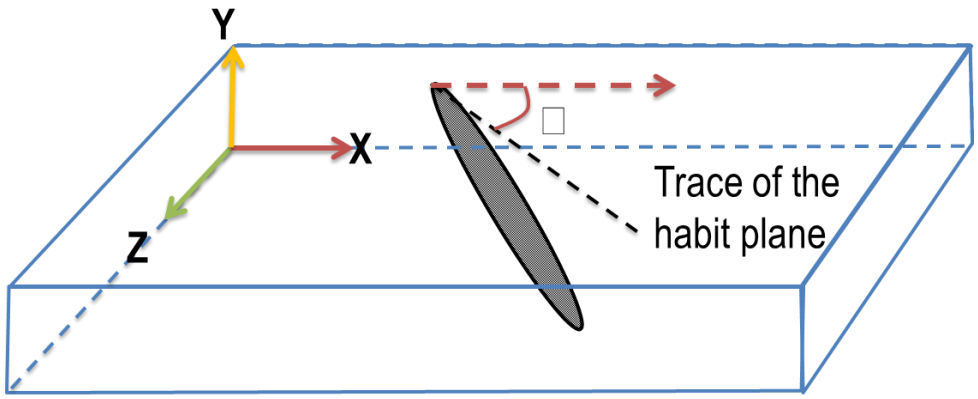
Microstructure

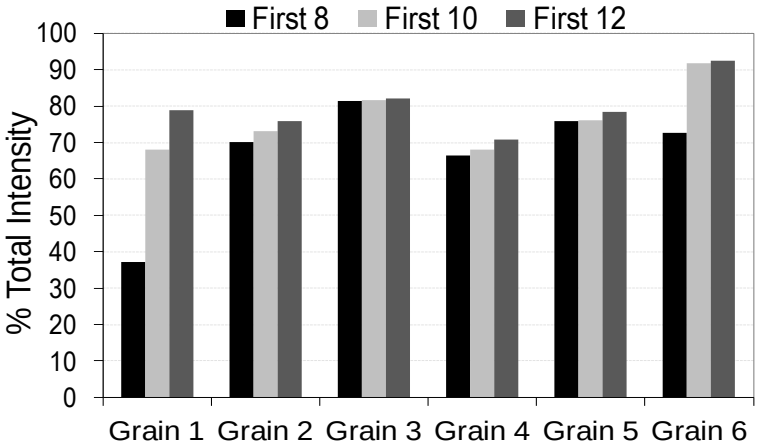
Austenite = 34%
Bainite = 66%

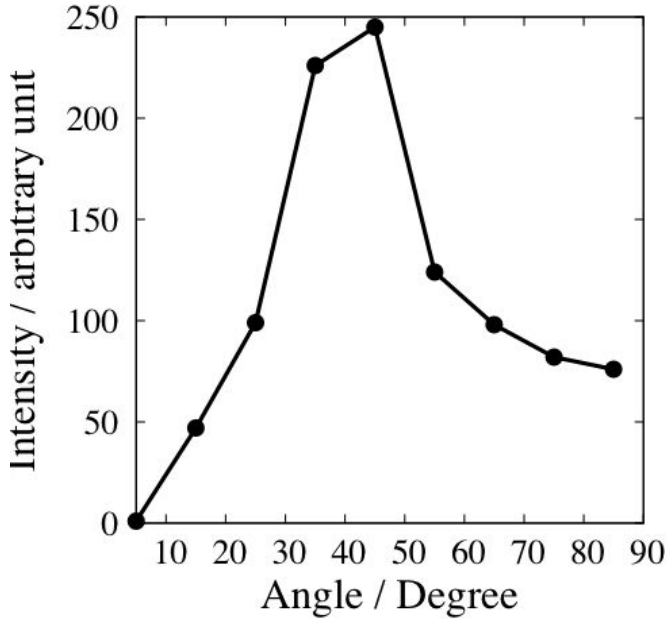


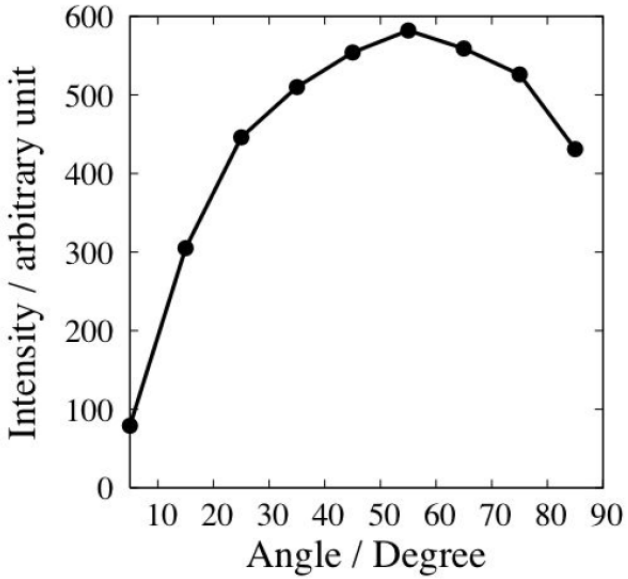
Alignment of bainite sheaves w.r.t RD

Prediction of sheaf alignment







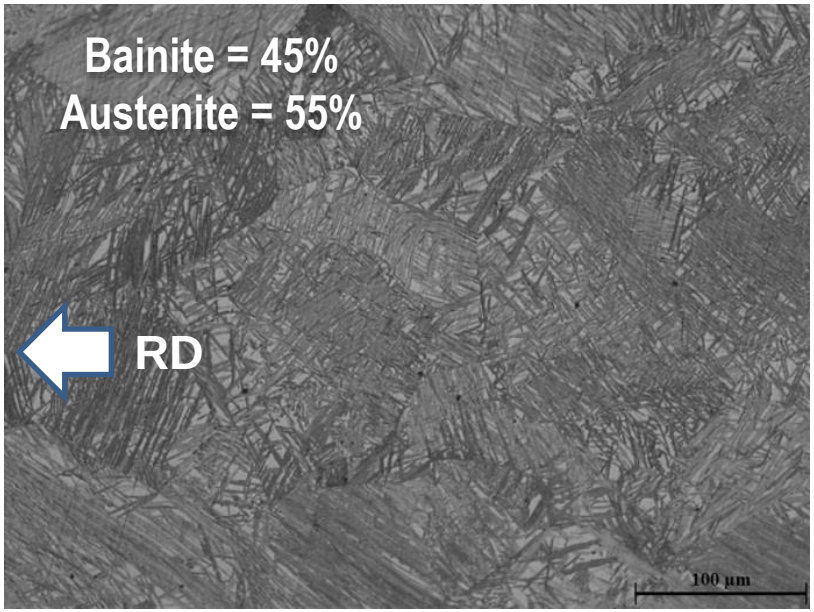


2 favoured variants

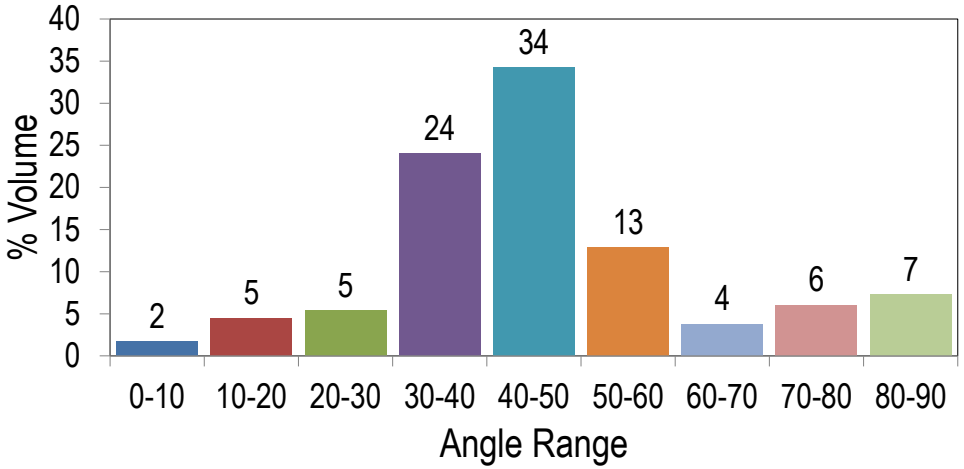
8 favoured variants

Kundu, Hase and Bhadeshia: Tata Search, (2009), 226

Orientation of sheaves under plastic strain

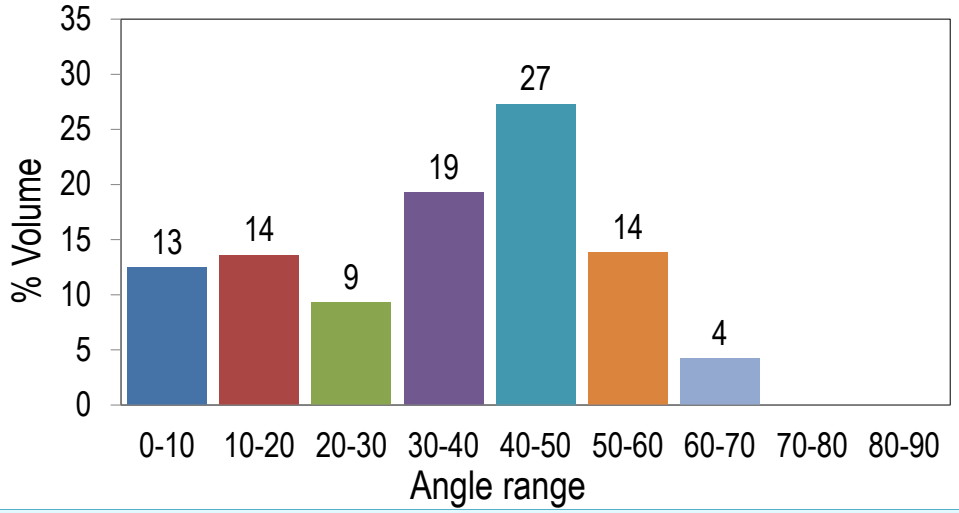


Microstructure



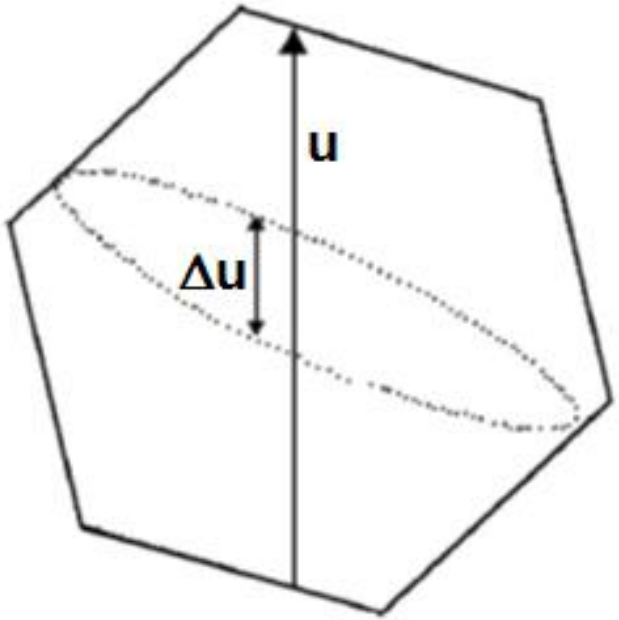
Alignment of bainite sheaves w.r.t RD

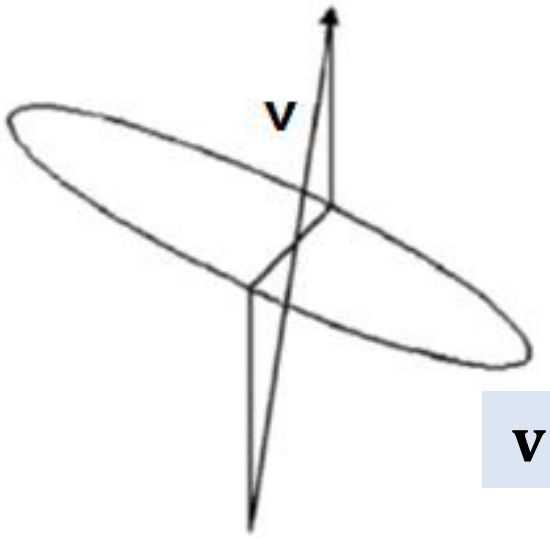
RD : Rolling Direction



Predicted distribution of most active slip planes w.r.t RD

Calculation of transformation strain



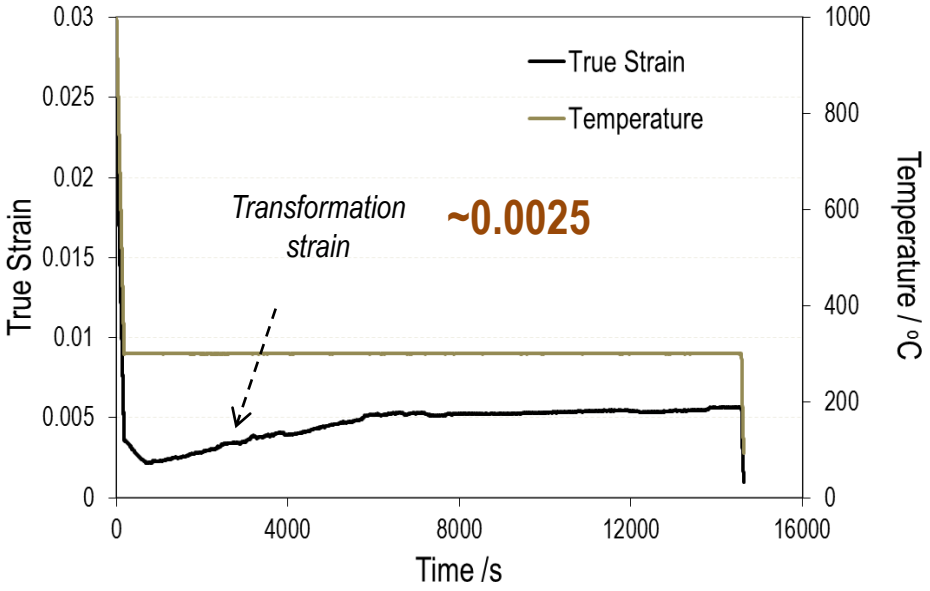


$$\mathbf{v} = \mathrm{P}\Delta\mathbf{u} + (\mathbf{u} - \Delta\mathbf{u})$$

$$\mathbf{v} = \sum_{k=1}^{n}\sum_{j=1}^{24} \mathbf{P}_j^k \, \Delta\mathbf{u}_j^k + \left(\mathbf{u} - \sum_{k=1}^{n}\sum_{j=1}^{24} \Delta\mathbf{u}_j^k\right)$$

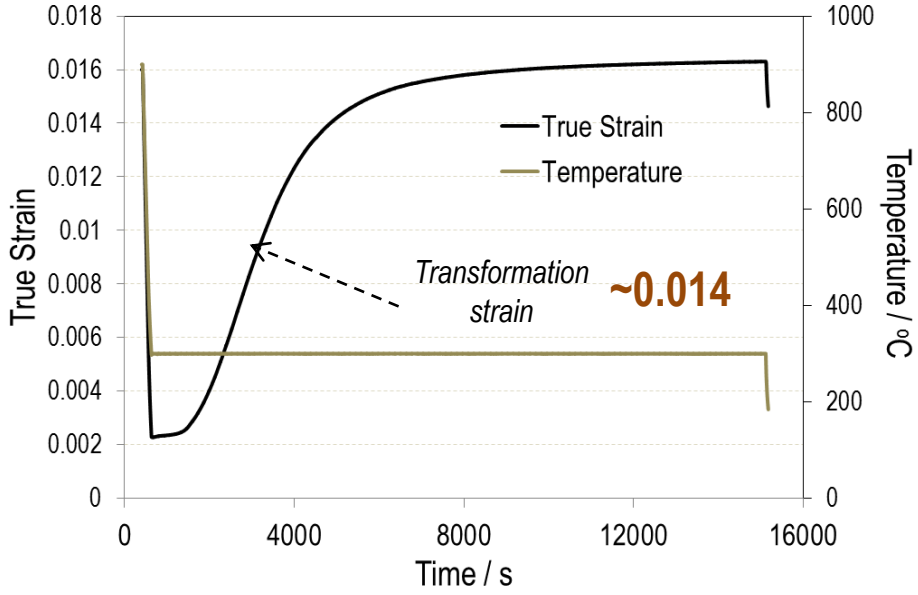
- Strain associated with each bainite plate interacts with each other.
- The shear strain gets cancelled but the volume strain remains.
- Stronger the variant selection higher is the transformation strain (?)

Transformation strain : no stress and compressive stress



No Load

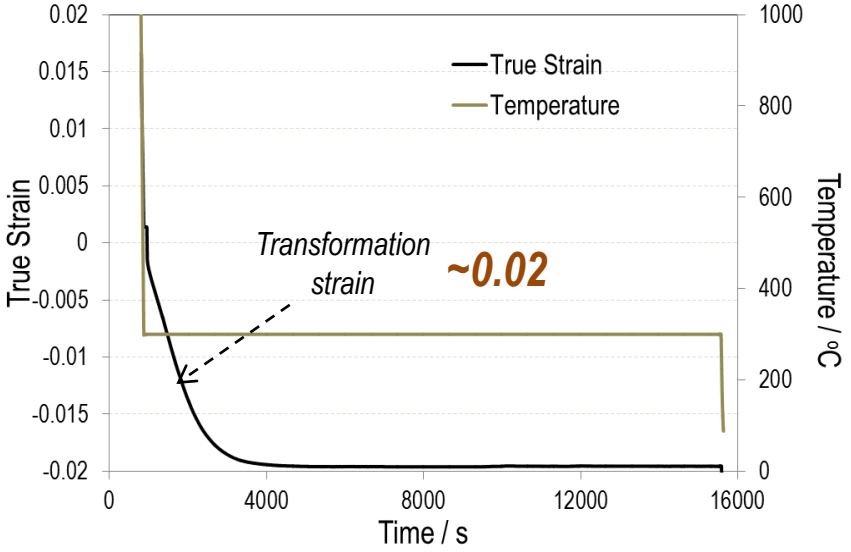
Shear Deformation : 0.229150
Volume Deformation : 0.009150
Total Deformation : 0.229367



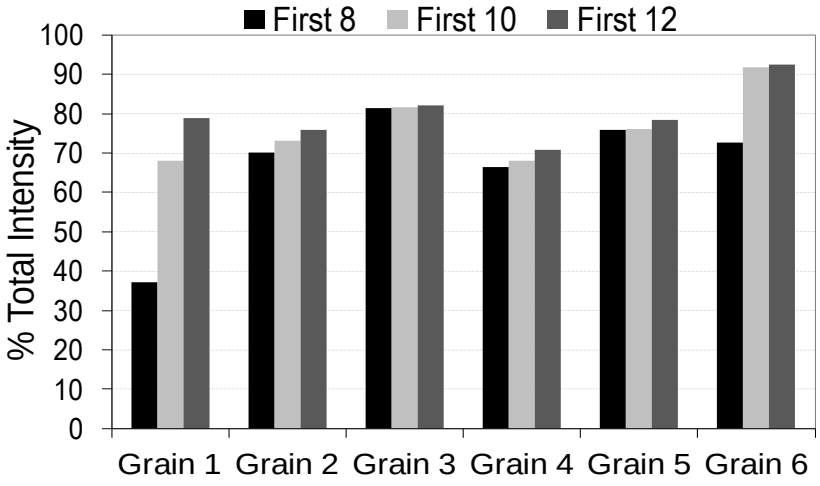
Experimental strain is measured in transverse direction

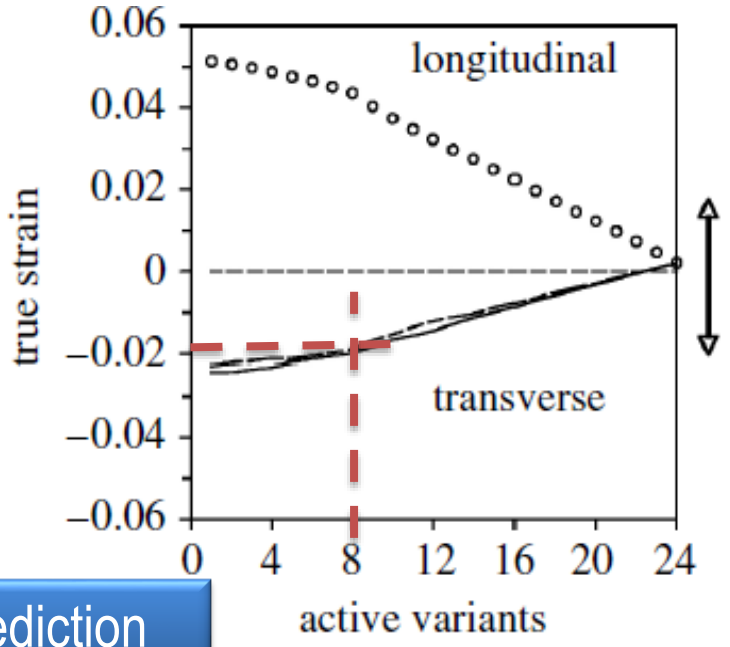
Compressive Load

Prediction of transformation plasticity



Experimental

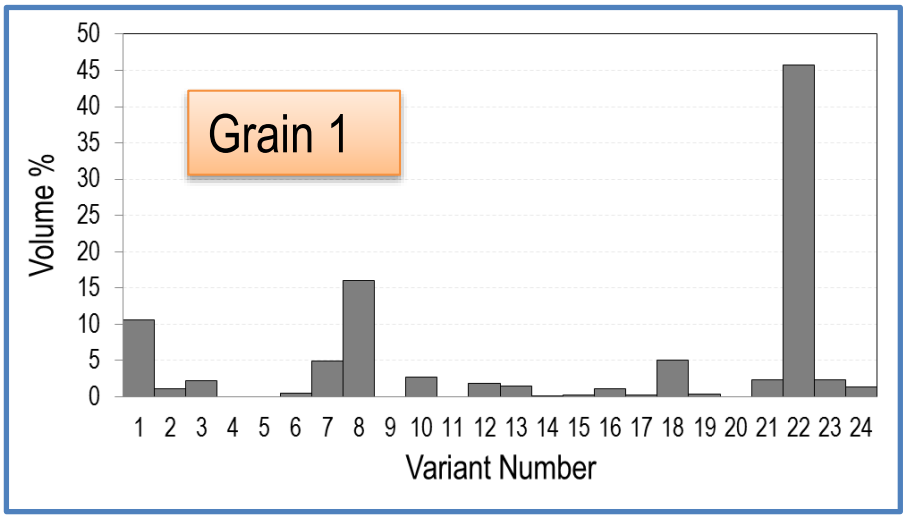


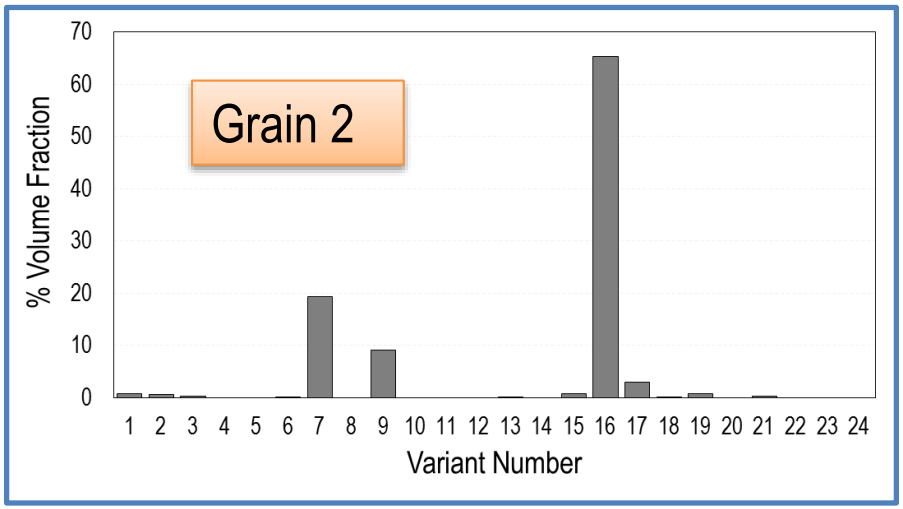


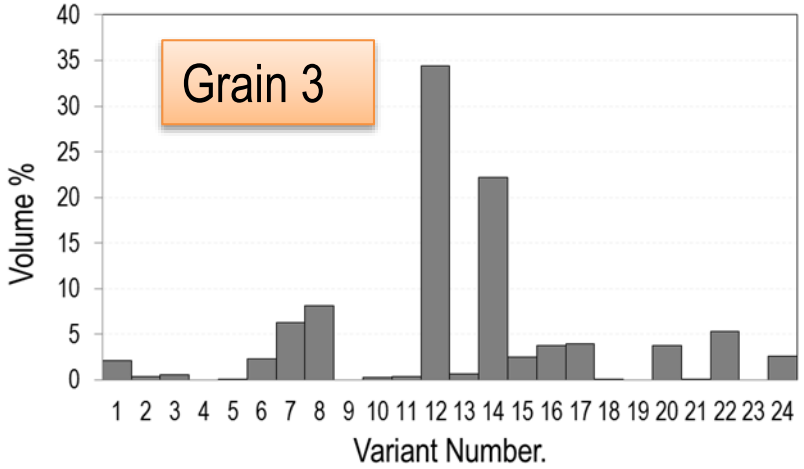
Prediction

Experimental strain is measured in transverse direction

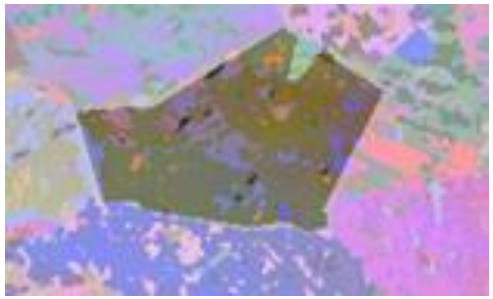
Variant selection from strained austenite



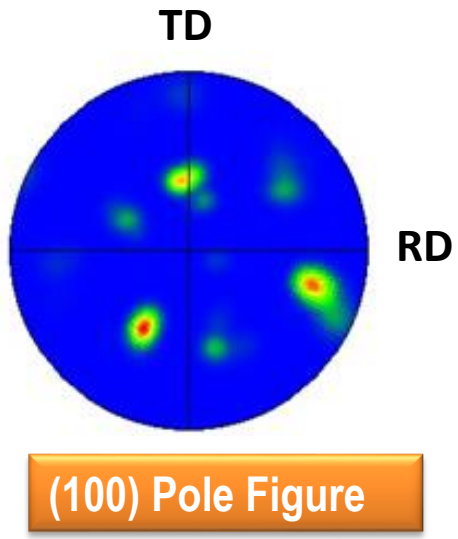




Variant distribution

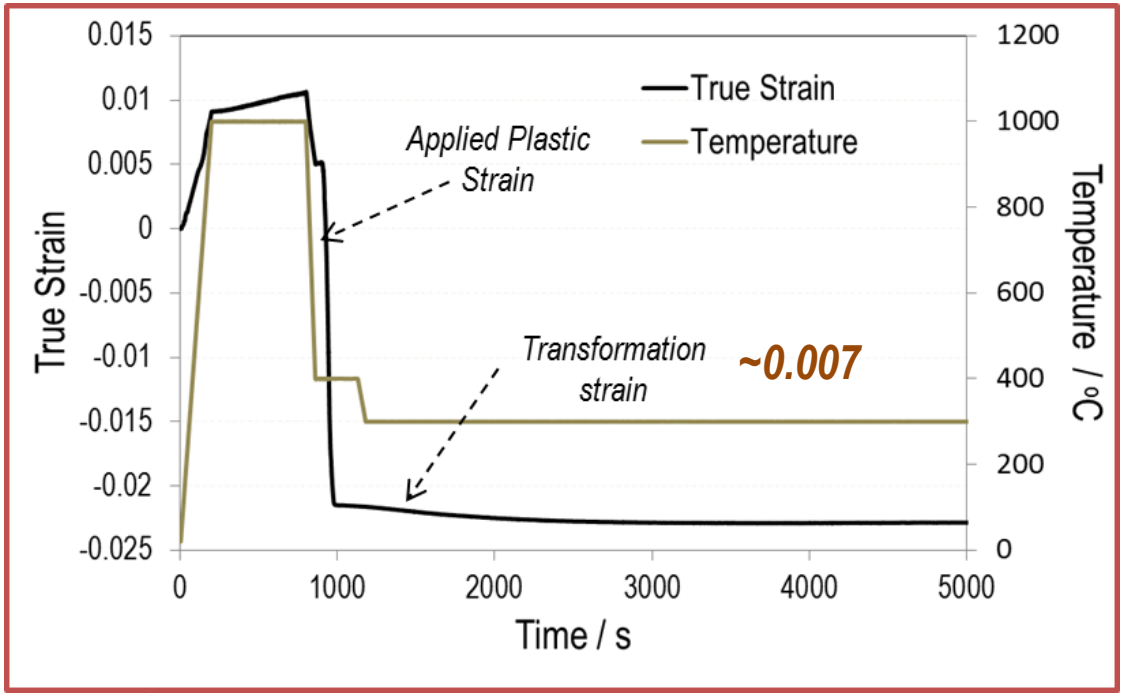


All Euler photo of one γ grain



(100) Pole Figure

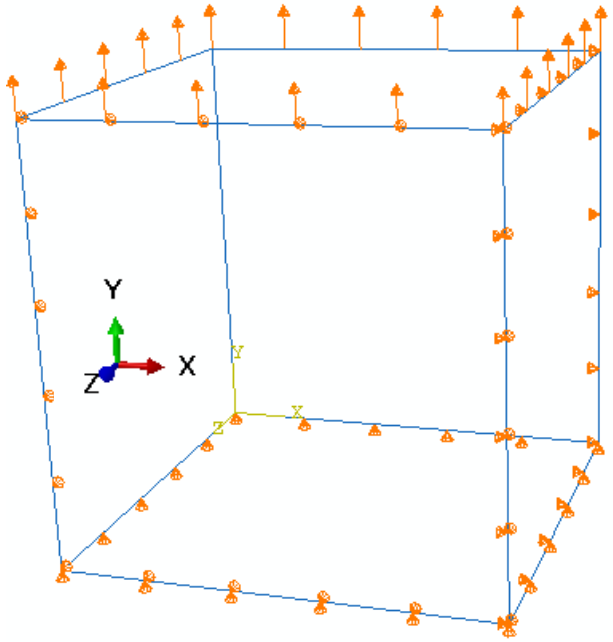
Bainite transformation from deformed austenite : transformation strain



Salient Points:

- There is very strong variant selection from strained austenite.
- Maximum 3 to 4 variants are present in each grain (examined ~20 grains).
- All the favoured variants are present in one “Bain Zone”.
- Transformation strain is extremely low.

FE Model



Dimension 1X1X1
Boundary Condition:

- U_1=0 at X=0
- U_2=0 at Y=0
- U_2=Δ at Y=1
- U_3=0 at Z=0

Material behaviour:

- Single crystal plasticity
- 12 slip systems of FCC crystal is considered.
- Hardening is ignored
- Interaction with neighboring grains is not considered
- Deformation only due to slip is modelled

Slip System

Slip Planes	Slip Directions
$(1\bar{1}1)$	$[110]$
	$[011]$
	$[10\bar{1}]$
(111)	$[0\bar{1}1]$
	$[1\bar{1}0]$
	$[10\bar{1}]$
$(11\bar{1})$	$[101]$
	$[1\bar{1}0]$
	$[011]$
$(\bar{1}11)$	$[101]$
	$[01\bar{1}]$
	$[110]$

Selection Criteria

- Variants with habit planes closest to the plane of maximum shear stress are selected

$$P_i = \sum_{j=1}^{4} \alpha_{ij} C_j$$

P_i=Chance of variant i to be selected

$$\alpha_{ij} = \begin{cases} 1 \text{ for } \theta = \theta_{\min} \\ 0 \text{ for } \theta \neq \theta_{\min} \end{cases}$$

θ = angle between habit plane normal of variant i and j^{th} slip plane normal

$C_j = \frac{\Gamma_j}{\max(\Gamma_i)}$ where, Γ_j = total shear on slip plane j

- Chance of variant selection is higher when the corresponding displacement direction is closest to the highest slip direction.

$$Q_i = \sum_{j=1}^{12} \beta_{ij} \gamma_j$$

Q_i=Chance of variant i to be selected

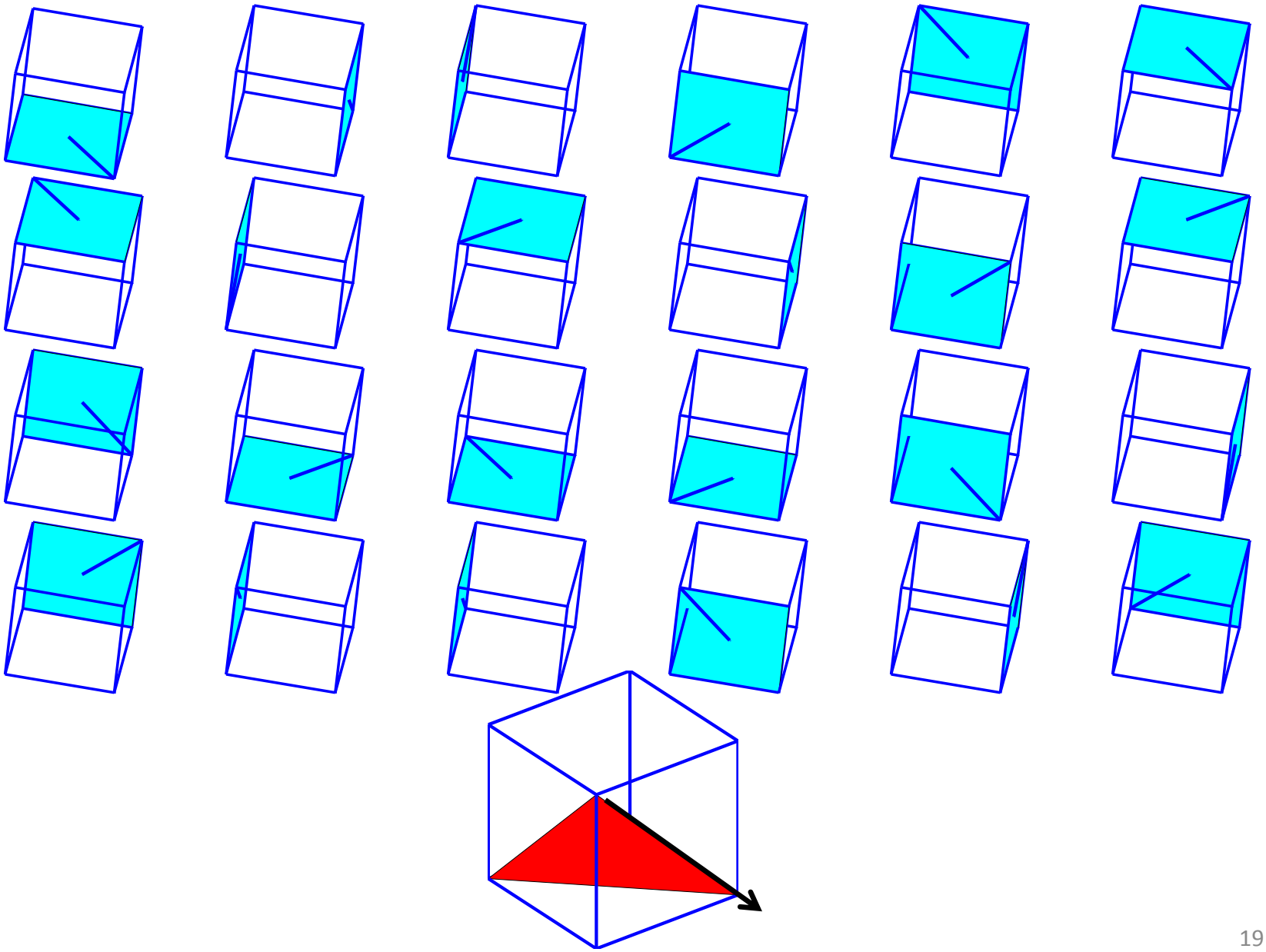
$$\beta_{ij} = \begin{cases} 1 \text{ for } \phi = \phi_{\min} \\ 0 \text{ for } \phi \neq \phi_{\min} \end{cases}$$

ϕ = angle between displacement direction of variant i and slip direction of slip system j

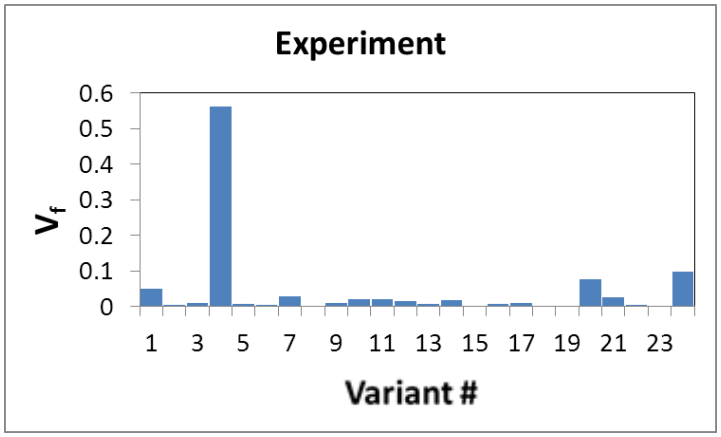
γ_j =plastic slip in j^{th} slip system

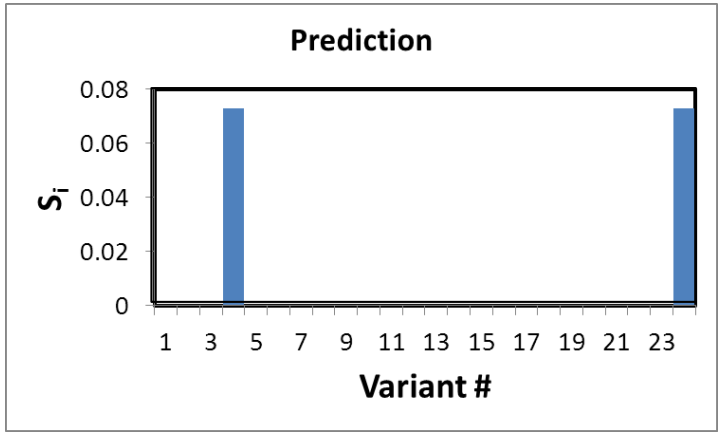
- Overall chance of variant i to be selected , $S_i = P_i Q_i$

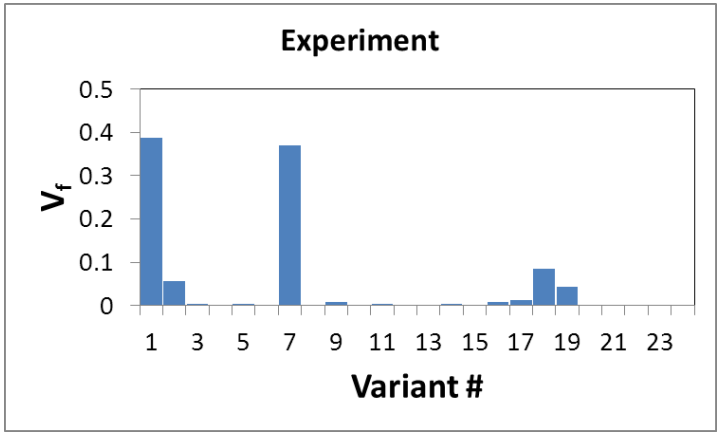
Selection Criterion: Visual

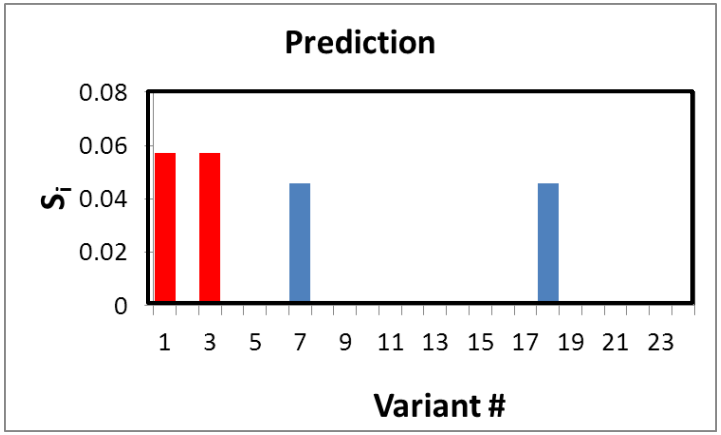


Comparison

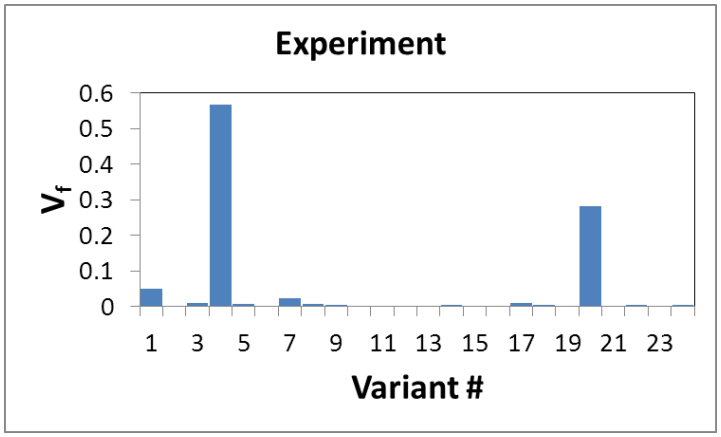

Experiment
V_f
0.6
0.5
0.4
0.3
0.2
0.1
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

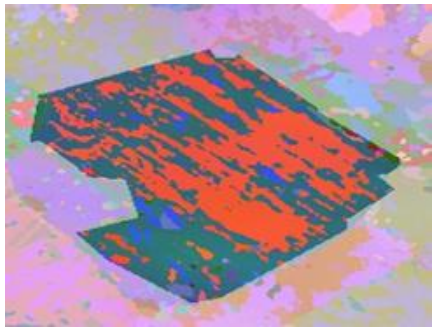

Prediction
S_i
0.08
0.06
0.04
0.02
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

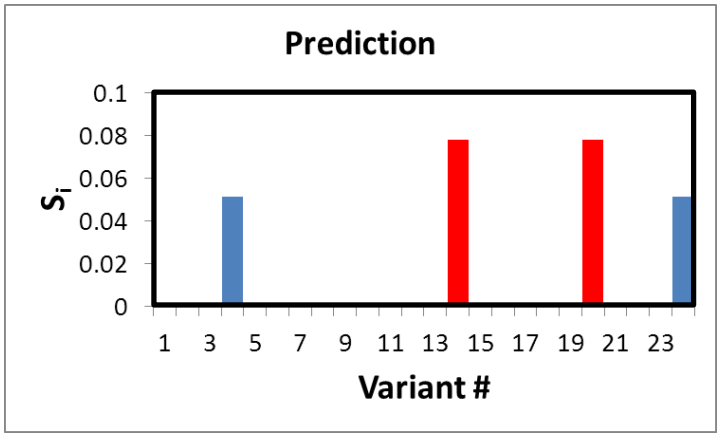

Experiment
V_f
0.5
0.4
0.3
0.2
0.1
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

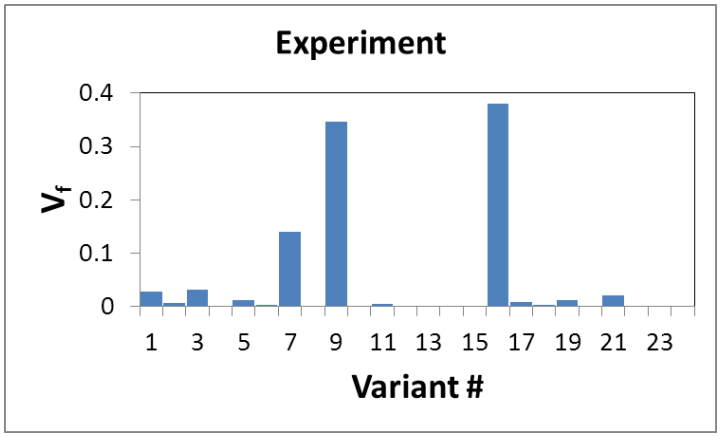

Prediction
S_i
0.08
0.06
0.04
0.02
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

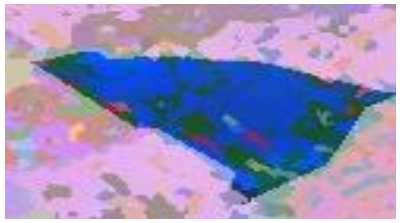
Comparison

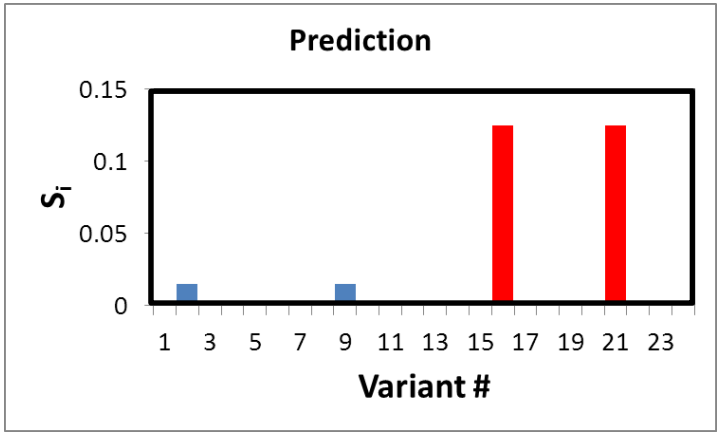

Experiment
V_f
0.6
0.5
0.4
0.3
0.2
0.1
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #



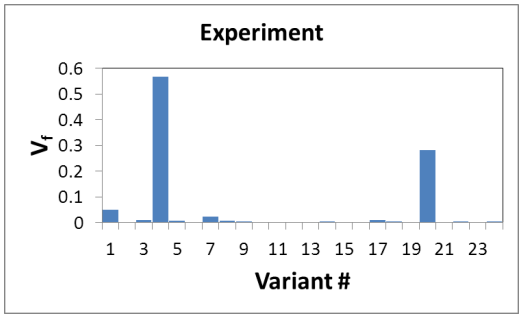

Prediction
S_i
0.1
0.08
0.06
0.04
0.02
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

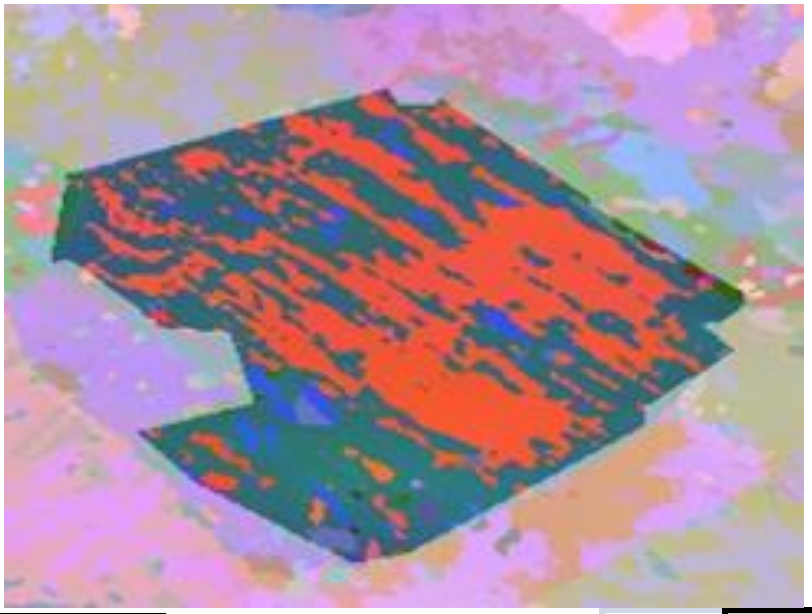

Experiment
V_f
0.4
0.3
0.2
0.1
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

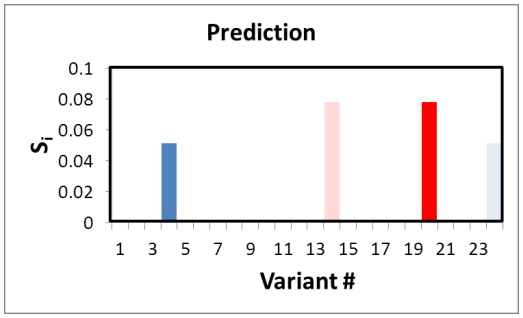



Prediction
S_i
0.15
0.1
0.05
0
1 3 5 7 9 11 13 15 17 19 21 23
Variant #

Selective Selection







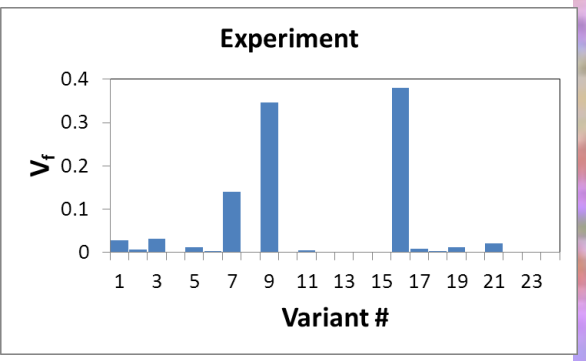
	4	14	20	24
4	0	45	49	11
14	45	0	11	38
20	49	11	0	45
24	11	38	45	0

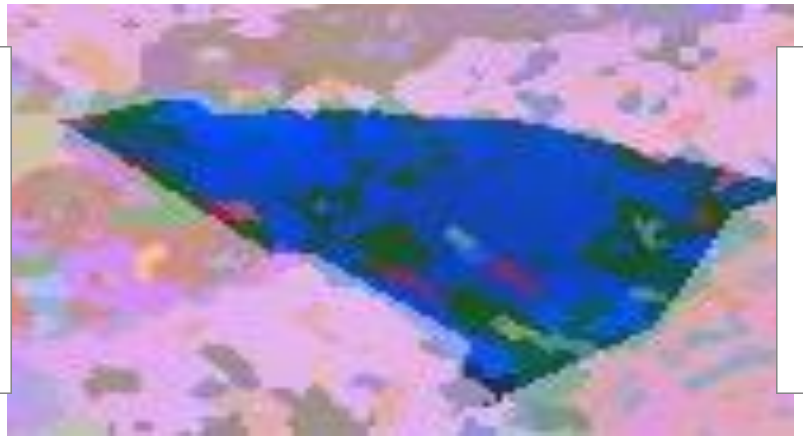
Angle between habit plane normal

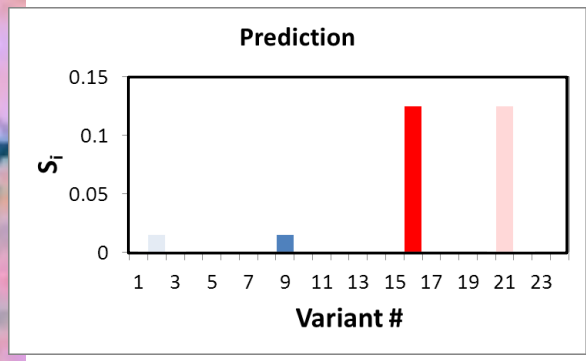
	4	14	20	24
4	0	60	3	58
14	60	0	58	60
20	3	58	0	60
24	58	60	60	0

Misorientation between variants

Selective Selection







	2	9	16	21
2	0	11	45	38
9	11	0	49	45
16	45	49	0	11
21	38	45	11	0

Angle between habit plane normal

	2	9	16	21
2	0	58	60	61
9	58	0	3	60
16	60	3	0	58
21	61	60	58	0

Misorientation between variants

Transformation strain in plastically deformed austenite

- Under stress variant selection tries to maximise the effect of external stress.
- As a result under tensile stress transformation strain in transverse direction is contraction type.
- Under strain variant selection tries to minimise the strain energy.
- As a result variants are selected to minimise total strain in the system.
- In both cases variants with minimum misorientation are selected to assist cooperative growth.

Conclusions

- Variants selection influences alignment of sheaves and transformation strain.
- Alignment of sheaves is dominant phenomenon under strain not under stress.
- A new mathematical model has been proposed to predict variant selection from strained austenite.
- Variant selection is much stronger under strain than stressed.
- The transformation strain is much smaller in case of variant selection under strain.