ZCO-53-2: Galvanizing Experiments
as part of the project
ZCO-53: Hot-Dip Galvanizing of Third Generation (3G) AHSS

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McMaster University ENGINEERING

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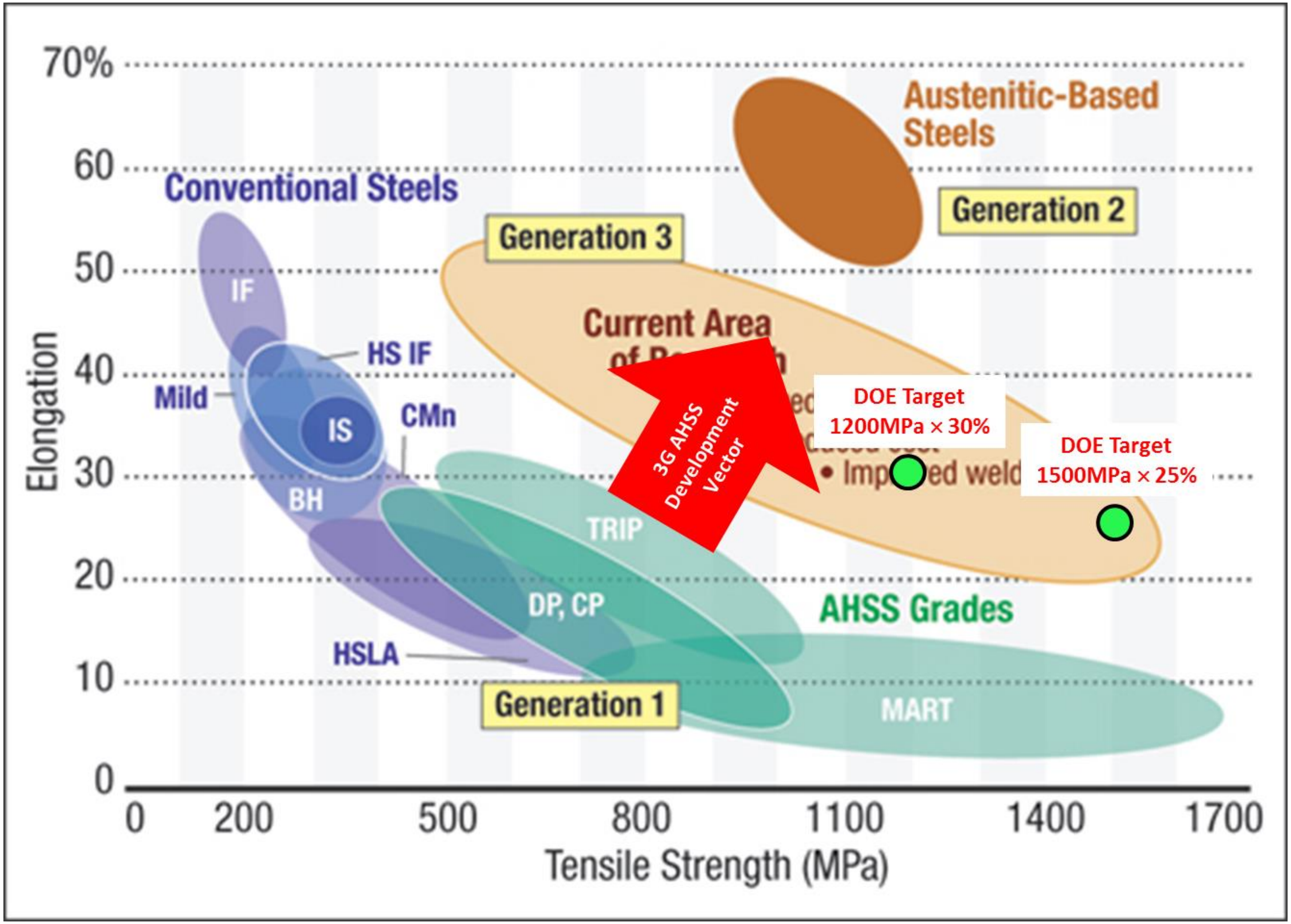
Project Objectives

- **Conduct galvanizing experiments using industrially solicited or custom fabricated medium Mn TRIP-assisted 3G-AHSS steels with the overall objectives of:**
  - **developing thermal processing treatments compatible with CGL capabilities which will;**
  - **meet 3G AHSS mechanical vs. US DOE targets 1200MPa UTS + 30% elongation (36,000 MPa%); 1500MPa UTS + 25% elongation (37,500 MPa%)**
  - **U.S. Auto targets: 1500MPa UTS + 20% elongation (30,000 MPa%)**
  - **developing a process window for the production of high quality galvanized coatings**

U.S. DOE Targets for 3G-AHSS Properties



C. Shutte: SAE Technical Paper 2015-01-0405 (2015), doi:10.4271/2015-01-0405

ZCO-53-2 Schedule

	M 1 – 6	M 6 – 12	M 12 – 18	M 18 – 24
Task 1: Microstructural and Mechanical Property Development				
steel A: 0.1C-6.3Mn-1.6Si-0.5Al				
steel B: 0.15C-6.5Mn-0.5Si-1.5Al				
steel D: 0.15C-6.1Mn-1Si-1Al				
steel E: 0.15C-6.1Mn-1Si-2Al				
steel F: 0.1C-6.3Mn-1.6Si-0.5Al-0.05Sn				
Task 2: Selective Oxidation and Hot-Dip Galvanizing Simulations				
Task 2a: Selective Oxidation				
steel A: 0.1C-6.3Mn-1.6Si-0.5Al				
steel B: 0.15C-6.5Mn-0.5Si-1.5Al				
steel D: 0.15C-6.1Mn-1Si-1Al				
steel E: 0.15C-6.1Mn-1Si-2Al				
Task 2b: Hot-Dip Galvanizing Simulations				
steel A: 0.1C-6.3Mn-1.6Si-0.5Al				
steel B: 0.15C-6.5Mn-0.5Si-1.5Al				
steel D: 0.15C-6.1Mn-1Si-1Al				
steel E: 0.15C-6.1Mn-1Si-2Al				
Task 3: Reports				

Steel Chemistries + Current Status

- Actively working on Steels A, B and E (6Mn + 1Si + Al) grades
- Steel F = Steel A + 0.05Sn – oxide modification

Steel	Type	C	Mn	Si	P	Al	Mo	Sn	Si/Mn
steel A	TRIP	0.21	6.26	1.55	0.007	0.52	0.077	--	0.25
steel B	TRIP	0.14	6.49	0.53	0.016	1.46	--	--	0.08
steel C	Q&P	0.2	1.8	1.5				--	0.83
steel D	TRIP	0.15	6.02	0.97	0.007	1.05	0.073	--	0.16
steel E	TRIP	0.15	6.09	0.97	0.007	1.89	0.084	--	0.16
steel F	TRIP	0.19	6.11	1.50	0.007	0.49	0.055	0.05	0.25

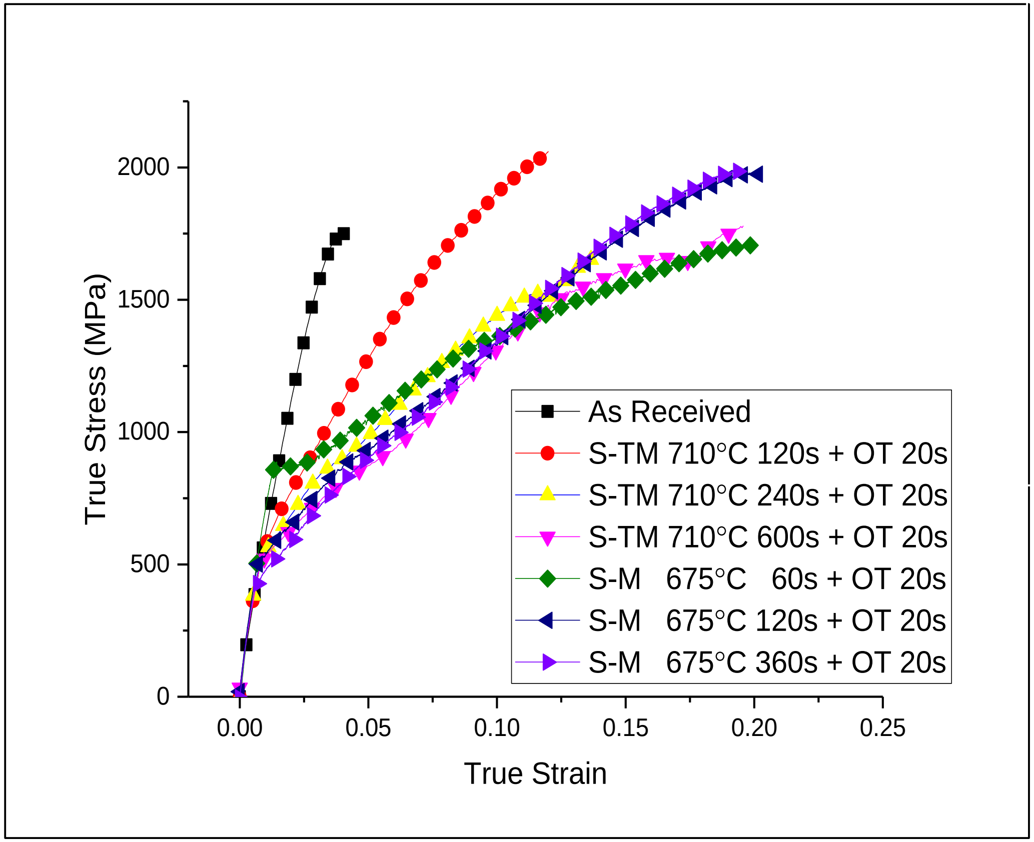
Steel A – Summary and Recent Progress

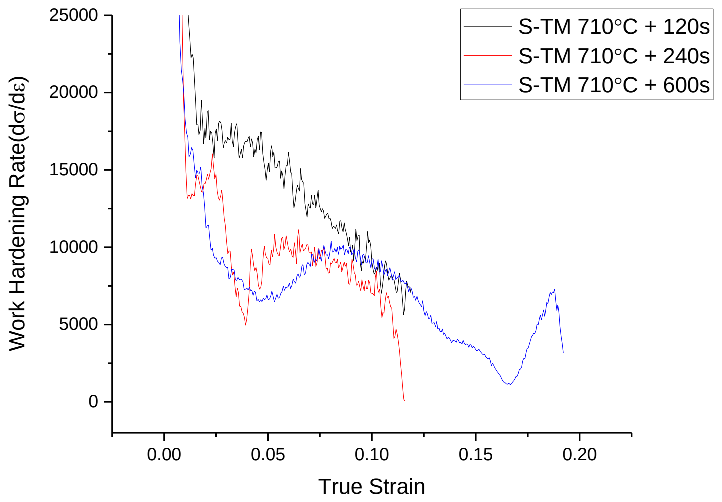
- **Have obtained high volume fractions of chemically stable retained austenite consistent with 3G-AHSS mechanical properties and consistent with high UTS U.S. DOE 3G target properties**
- **Examined effect of 460°C OT time on the properties of selected S-TM and S-M samples –mechanical properties sensitive to longer hold at bath temp**
- **TEM analysis at higher magnification to perform**
  - **Microstructural characterization (especially phase morphology)**
  - **Orientation relationship (OR)**
  - **EDS analysis of carbide particles**

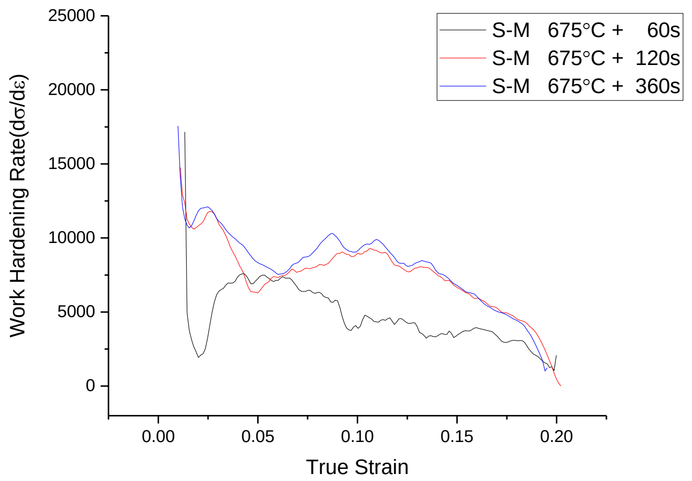
Steel A – Tensile Test Results (Effect of IBT)

Sample ID	Yield Strength (MPa)	Ultimate Tensile Strength, UTS (MPa)	% elongation	UTS × % elongation (MPa %)
S-TM(20s) 710°C +120s	600	1828	11.4	20,839
S-TM(60s)710°C+120s	859	1409	15.5	21,839
S-TM(120s)710°C+120s	960	1370	17.5	23,975
S-TM(20s) 710°C +240s	540	1458	13.6	19,828
S-TM(60s)710°C +240s	535	1566	10	15,660
S-TM(120s)710°C +240s	510	1612	12	19,344
S-M(20s) 675°C +60s	830	1465	20.5	30,032
S-M(60s) 675°C +60s	922	1290	19	24,510
S-M(120s) 675°C +60s	960	1345	18	24,210
S-M(20s) 675°C +120s	640	1535	28	42,980
S-M(60s) 675°C +120s	880	1285	19.5	25,057
S-M(120s) 675°C +120s	898	1303	19.5	25,408

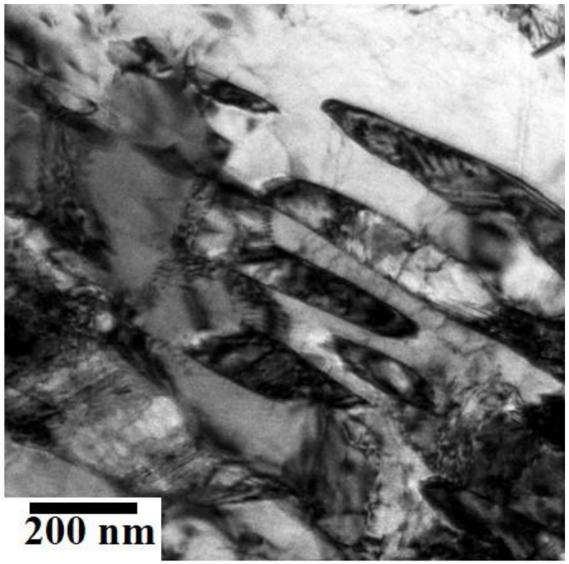
Steel A – True Stress vs True Strain (20s OT)







Steel A – TEM Analysis (S-M 675°C+120s)



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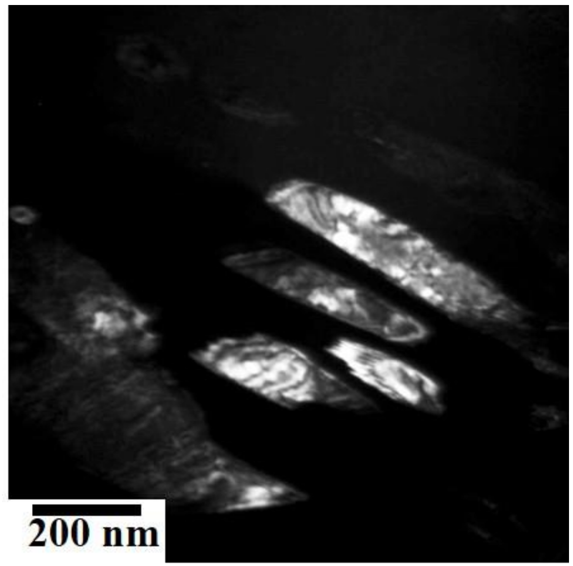

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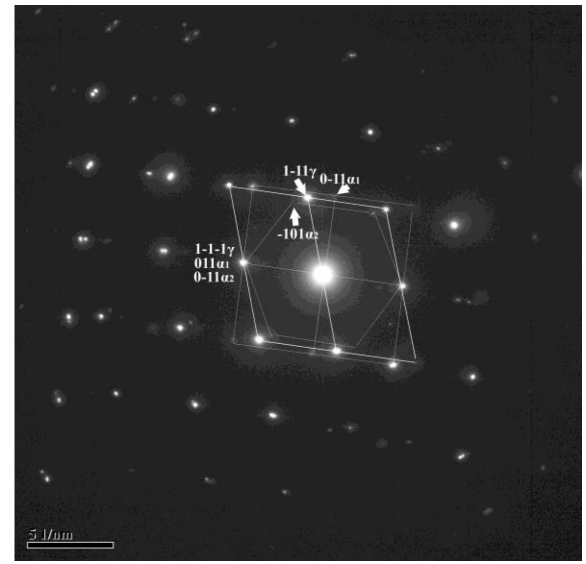
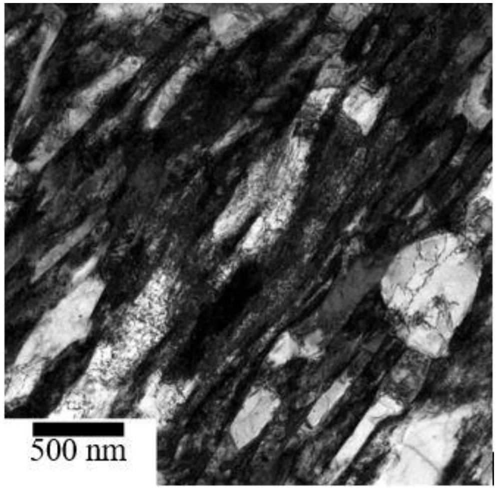


SAD patterns

Steel A – TEM Analysis (S-M 710°C+360s)



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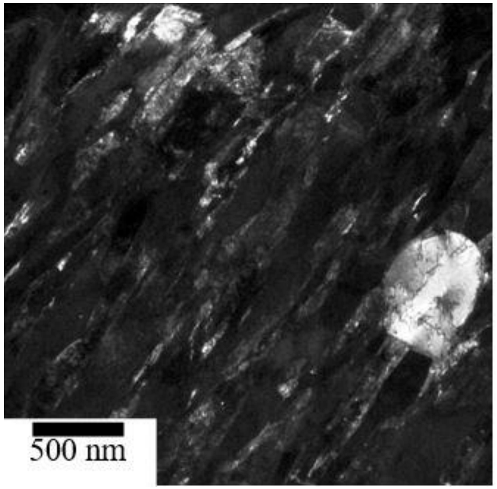

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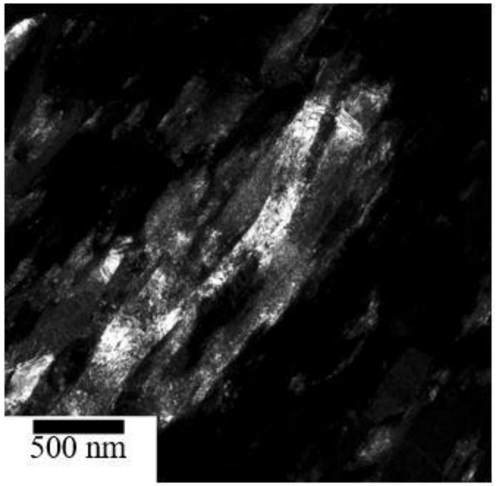

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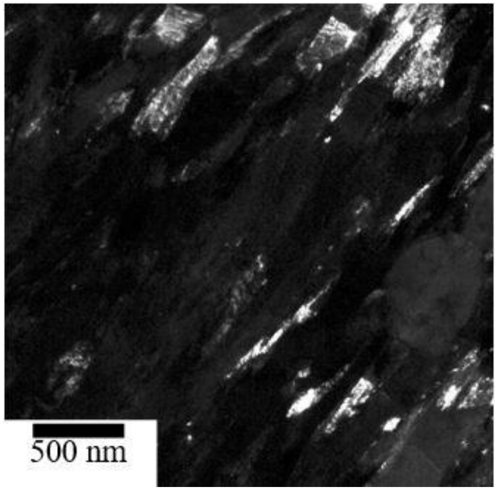

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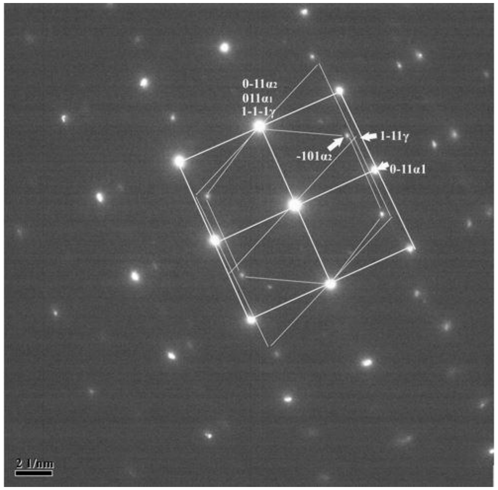
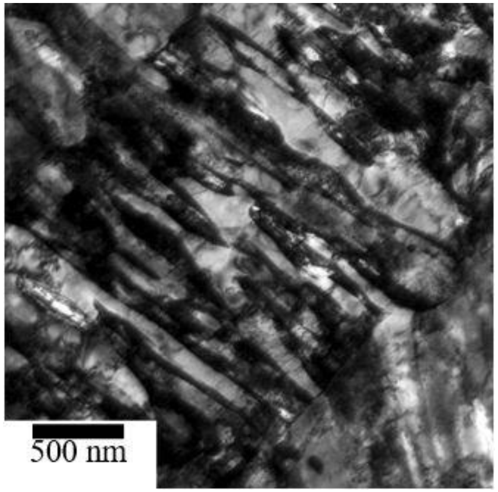


SAD patterns

Steel A – TEM Analysis (S-M 675°C+480s)



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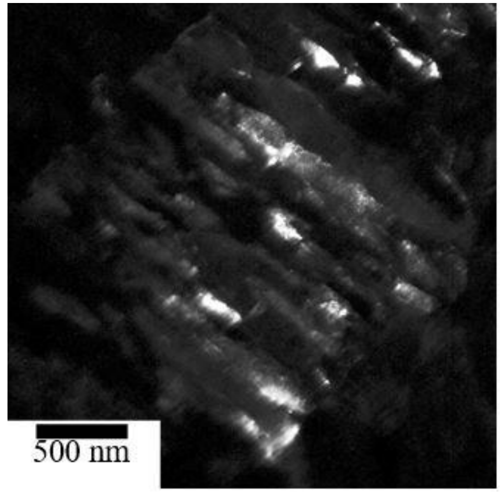

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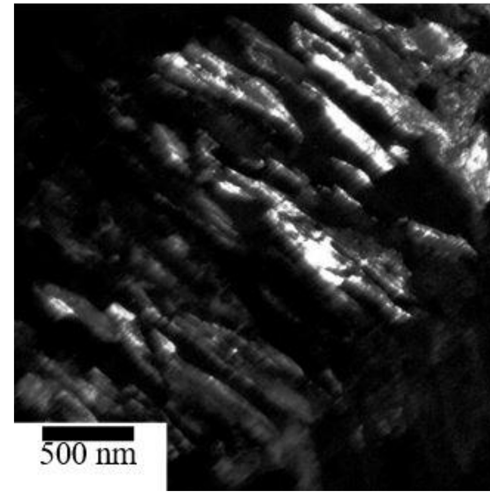

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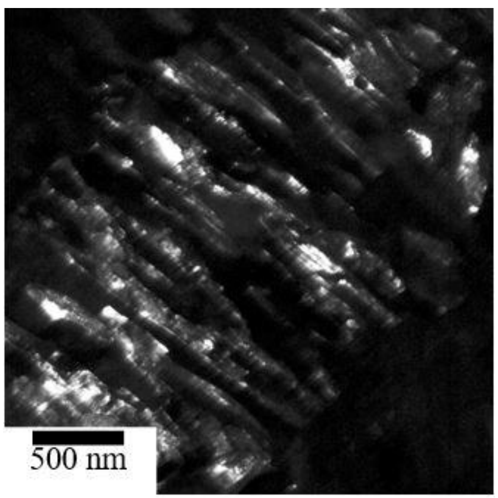

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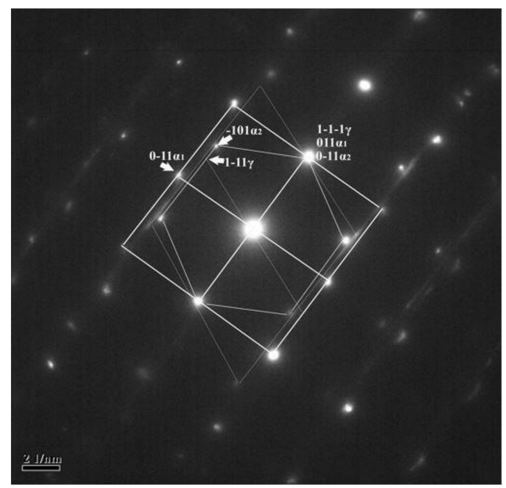


SAD patterns

Steel A – TEM Analysis (OR)

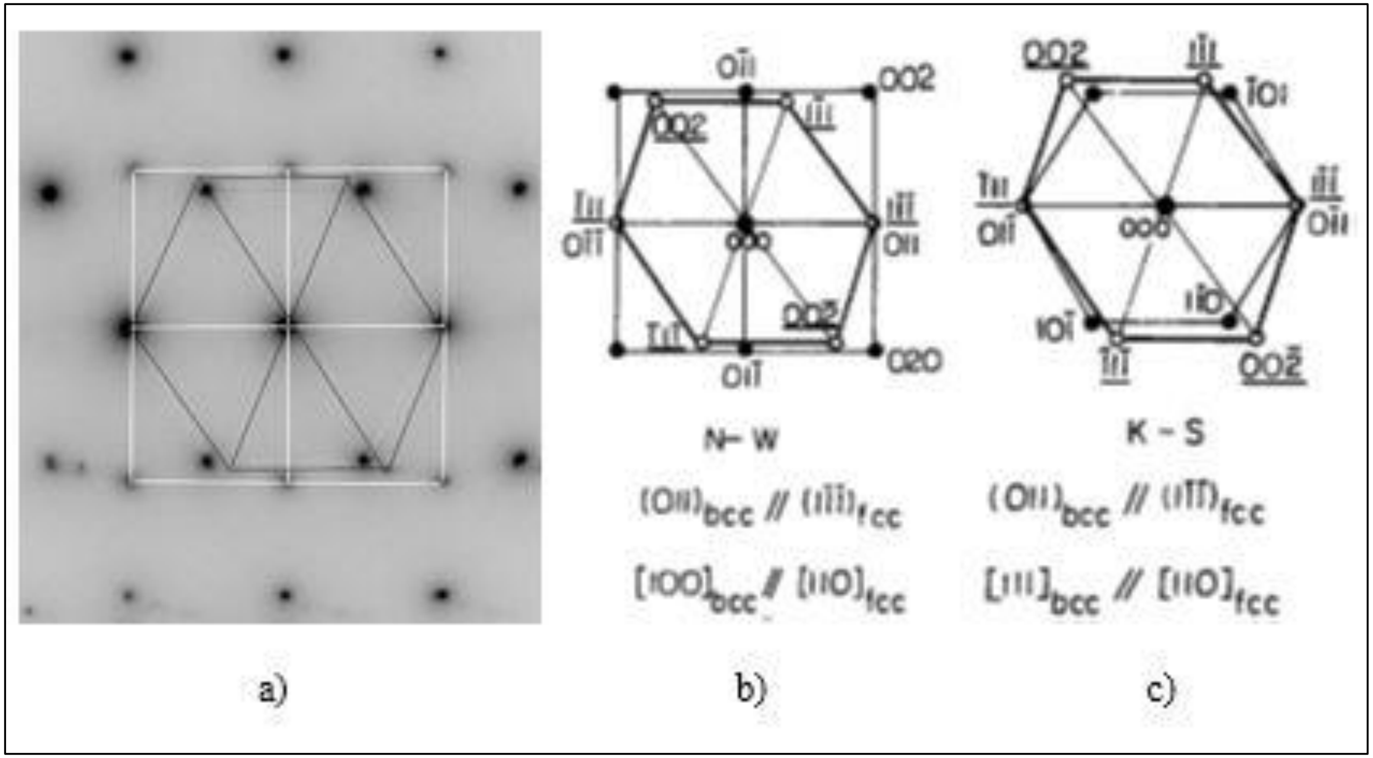
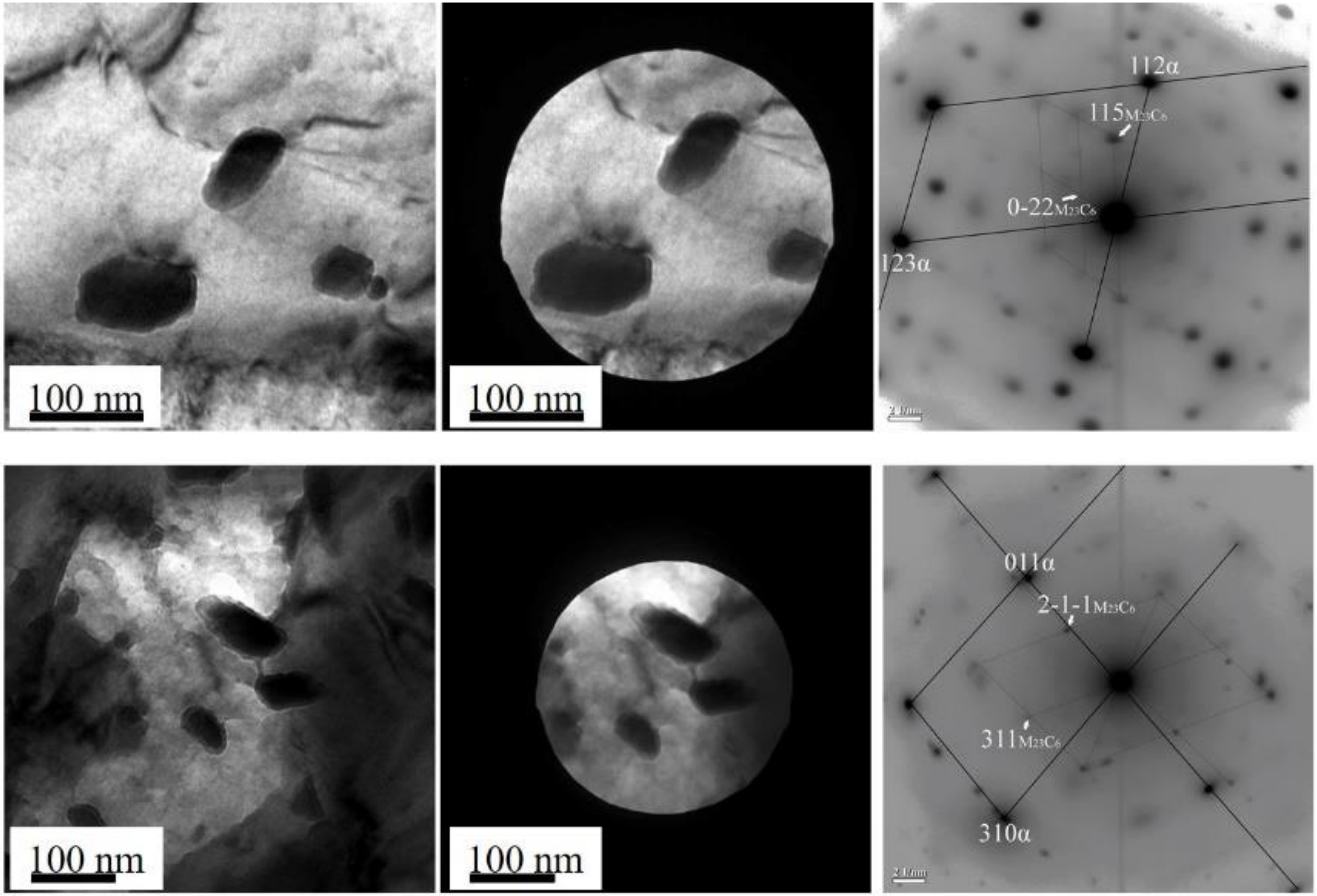


Fig.: a) SAD patterns of S-M 675°C + 480s sample and schematic representation of SAD patterns for b) Nishiyama-Wasserman (N-W) and c) Kudrjumov-Sachs (K-S) orientation relationship.

Steel A – TEM Analysis (Carbide Particles)



Steel A – TEM Analysis (Carbide Particles)

Average Carbide Particle and Matrix Composition from EDS Spot Analysis (at.%)

Element / Sample	C	Al	Si	Ti	Cr	Mn	Fe	Ratio of (Cr+Mn) /C
Particle								
675°C for 480s	4.79	0.55	1.78	0.04	**2.84**	**12.98**	77.02	3.31
675°C for 600s	7.99	1.85	2.43	0.03	**2.33**	**11.43**	73.93	1.72
710°C for 360s	3.18	0.57	1.48	0.02	**3.03**	**11.25**	80.47	4.48
710°C for 600s	7.93	0.47	1.98	0.03	**2.79**	**12.16**	74.67	1.88
Matrix								
675°C for 480s	0.32	0.67	2.71	0	0.60	3.80	91.90	
675°C for 600s	1.44	0.68	3.67	0	0.57	5.22	88.42	
710°C for 360s	0.91	0.53	1.98	0	0.51	5.06	91.03	
710°C for 600s	1.04	1.04	3.16	0	0.48	4.32	89.96	

Steel A – Summary and Future Work

- **TEM analysis to determine the effect of stacking fault energy on plasticity enhancing mechanisms (TRIP/TWIP).**
- **APT analysis to evaluate Mn and C partitioning in retained austenite**
- **Determine the effect of intercritical annealing temperature on properties**
- **Selective oxidation and reactive wetting tests – with and without Sn additions (steels A and F)**

Steel D – Current Status

- **The transfer bars for Steel D have been received and machined to dilatometry samples**
  - **dilatometry studies currently underway at CanMaterials – next GAP meeting**
- **Will be defining intercritical annealing parameters from these results**
  - **retained austenite and properties vs. intercritical annealing parameters**

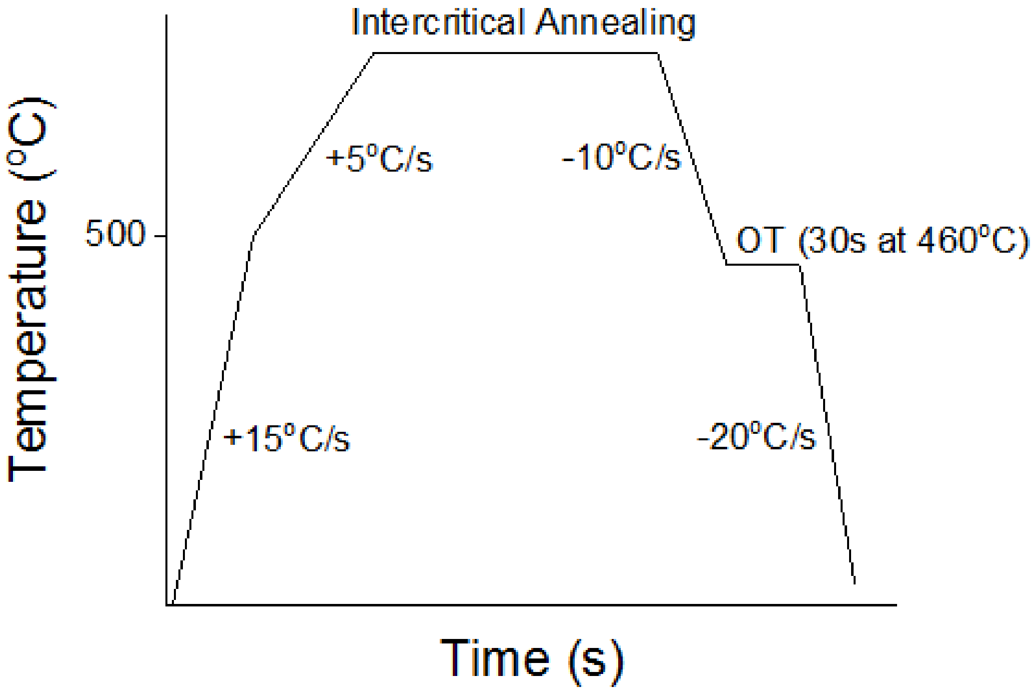
Steel E – Current Status

- Three samples have achieved the required mechanical property targets:
  - AR-665°C-120s (31,200 MPa%)
  - AR-665°C-240s (33,600 MPa%)
  - MF-665°C-240s (30,900 MPa%)
- Revised heat treatment matrix for XRD/SEM coupons is complete
  - Many samples have achieved ~30% retained austenite
- Selected heat treatments were performed on panels for tensile samples
  - Panels have been sent for machining, tensile tests to be performed by the end of October

Steel E – Current Status

- **Mechanical testing on selected samples from the revised matrix is complete.**
  - **further analysis of tensile behaviour using Digital Image Correlation is in progress.**
- **Selected samples have undergone oxidation trials and are being prepared for XPS analysis.**

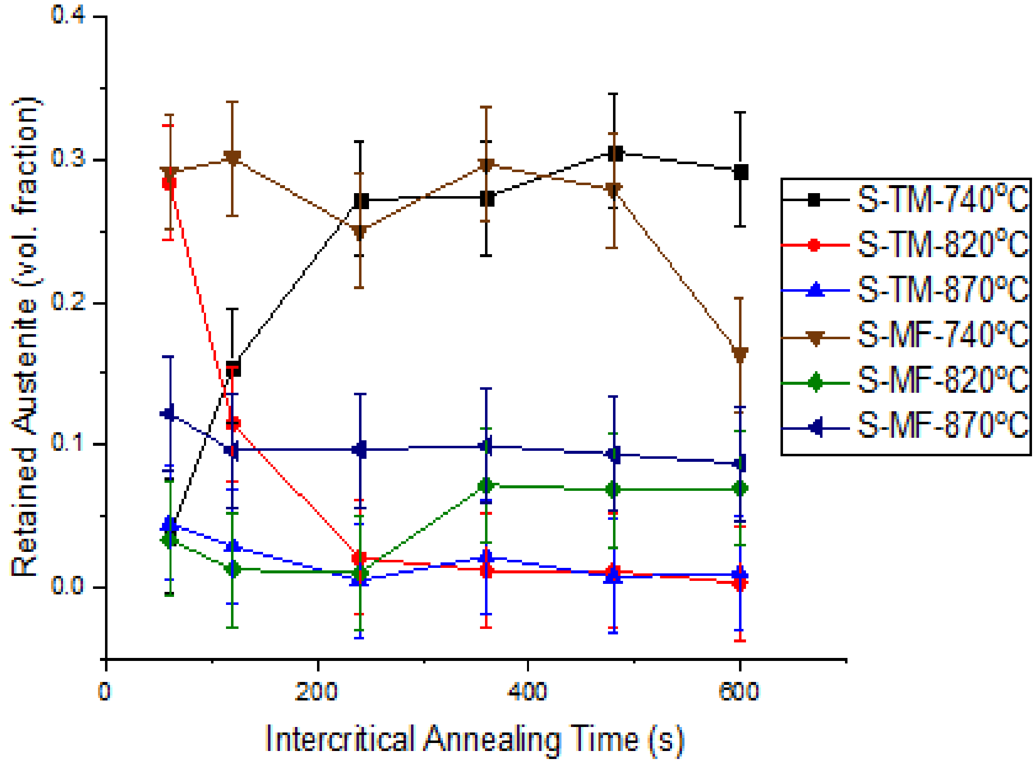
Steel E – Experimental Plan



Target Volume Fraction of Intercritical Austenite	Intercritical Annealing Temperature (°C)	Intercritical Annealing Time (s)
0.25	740	60, 120, 240, 360, 480, 600
0.50	820	
0.75	870	

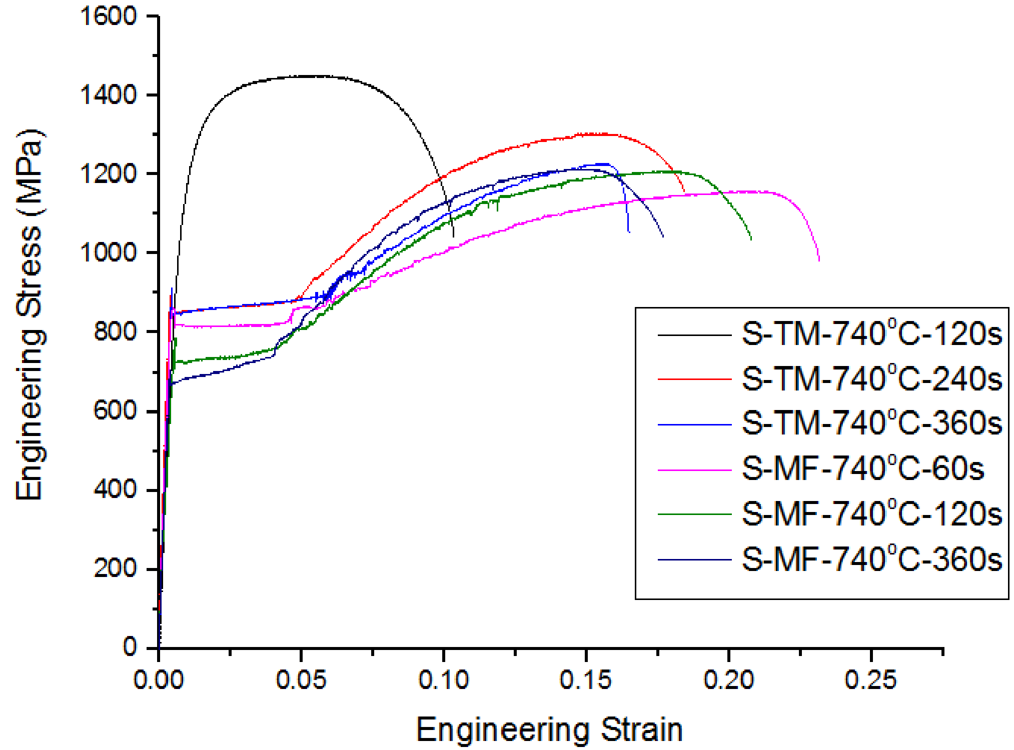
Steel E – Retained Austenite

- Promising results for samples annealed at 740°C.
  - Longer times required for S-TM samples.
- IA temperatures of 820°C and 870°C likely too high to achieve target.
  - Retained austenite not chemically stable.



Steel E – Uniaxial Tensile Tests

- **S-TM-740°C-120s typical of a lightly tempered martensite.**
- **Remaining samples displayed yield point elongation but improved ductility.**
- **Preliminary findings from DIC suggest PLC bands formed during deformation.**



Steel E – Uniaxial Tensile Tests

Sample Name	UTS x Elongation (MPa%)		Sample Name	UTS x Elongation (MPa%)
As-Received	7,560		Martensite-Ferrite	16,000
Initial Matrix			Initial Matrix	
S-TM-665°C-120s	31,200		S-MF-665°C-120s	28,840
S-TM-665°C-240s	33,600		S-MF-665°C-240s	30,900
Revised Matrix			Revised Matrix	
S-TM-740°C-120s	15,000		S-MF-740°C-60s	26,650
S-TM-740°C-240s	23,400		S-MF-740°C-120s	25,000
S-TM-740°C-360s	19,800		S-MF-740°C-360s	21,500

Steel E – Uniaxial Tensile Tests

- **Annealing treatments from the initial matrix resulted in better mechanical properties than the annealing treatments from the revised matrix.**
  - **No samples met the 30,000-36,000MPa% envelope.**
- **This suggests that samples annealed according to the revised matrix had less chemically stable retained austenite**
- **Need to further explore relationship between IAT and properties, particularly %elongation**

Steel E – Future Work

- Interrupted tensile tests
- Transmission Electron Microscopy:
  - Analysis of fine structures
  - Carbide morphology and location
  - Elemental line scans across phase boundaries
- Atom Probe Tomography:
  - Partitioning of alloying elements across phase boundaries
- Effect of IAT on mechanical properties
- Reactive wetting trials