Progress Review

Thermomechanical fatigue of Boeing 60-NiTi

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Progress overview

- Cumulative results for water jet processed SMA strips
- First results for EDM processed SMA strips - Problems related to heat treatment performed in air vs. in vacuum
- Influence of environment during heat treatment on fracture surfaces
- Recommendations for further testing

Cumulative results for water jet processed SMA strips

After testing all water jet processed specimens and after identification of erroneous data due to experimental malfunctions (creep-like behavior, grip slip, non-uniform test gauge of specimens), 4 tables were generated to collect the testing parameters such as: and also significant generated data:

- Specimen number
- Specimen thickness
- Applied stress level

and also significant generated data such as:

- Recoverable strain half way through the life of the specimens
- Plastic strain half way through the life of the specimens
- Recoverable strain at failure
- Plastic strain at failure

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Comprehensive results for water jet processed specimens for heat treatment #1

Table 1 is ordered according to increasing sample thickness

HT1 - 1 hr @ 850°C, 1 hr @ 450°C							
Specimen number	**Thickness (mils)**	**Applied stress (MPa)**	**Cycles to failure Nf**	**Recoverable strain @ 1/2 Nf**	**Plastic strain @ 1/2 Nf**	**Recoverable strain @ Nf**	**Plastic strain @ Nf**
3	**5**	204	6896	0.01073	0.00257	0.01063	0.00685
10	**5**	100	67571	0.00464	0.00861	0.0046	0.01457
2	**10**	250	3838	0.01209	0.02585	0.01329	0.03511
5	**10**	90	57598 (run out)	0.00583	0.01337	0.0048	0.0323
7	**15**	243	5251	0.0106	0.026	0.0104	0.03667
9	**15**	100	55811	0.00383	0.00726	0.00427	0.01074
1	*Damaged during preliminary testing*						
4	*Invalid results (computer malfunction)*						
6	*MTS tested*						
8	*Invalid results (computer malfunction)*						

Table 2 is ordered according to increasing applied stress level

HT1 - 1 hr @ 850°C, 1 hr @ 450°C							
Specimen number	**Thickness (mils)**	**Applied stress (MPa)**	**Cycles to failure Nf**	**Recoverable strain @ 1/2 Nf**	**Plastic strain @ 1/2 Nf**	**Recoverable strain @ Nf**	**Plastic strain @ Nf**
5	10	**90**	57598 (run out)	0.00583	0.01337	0.0048	0.0323
9	15	**100**	55811	0.00383	0.00726	0.00427	0.01074
10	5	**100**	67571	0.00464	0.00861	0.0046	0.01457
3	5	**204**	6896	0.01073	0.00257	0.01063	0.00685
7	15	**243**	5251	0.0106	0.026	0.0104	0.03667
2	10	**250**	3838	0.01209	0.02585	0.01329	0.03511
1	*Damaged during preliminary testing*						
4	*Invalid results (computer malfunction)*						
6	*MTS tested*						
8	*Invalid results (computer malfunction)*						

Remarks: Specimen #3 HT1 has a relatively small amount of accumulated plastic strain compared to the rest of the specimens

Comprehensive results for water jet processed specimens for heat treatment #2

Table 1 is ordered according to increasing sample thickness

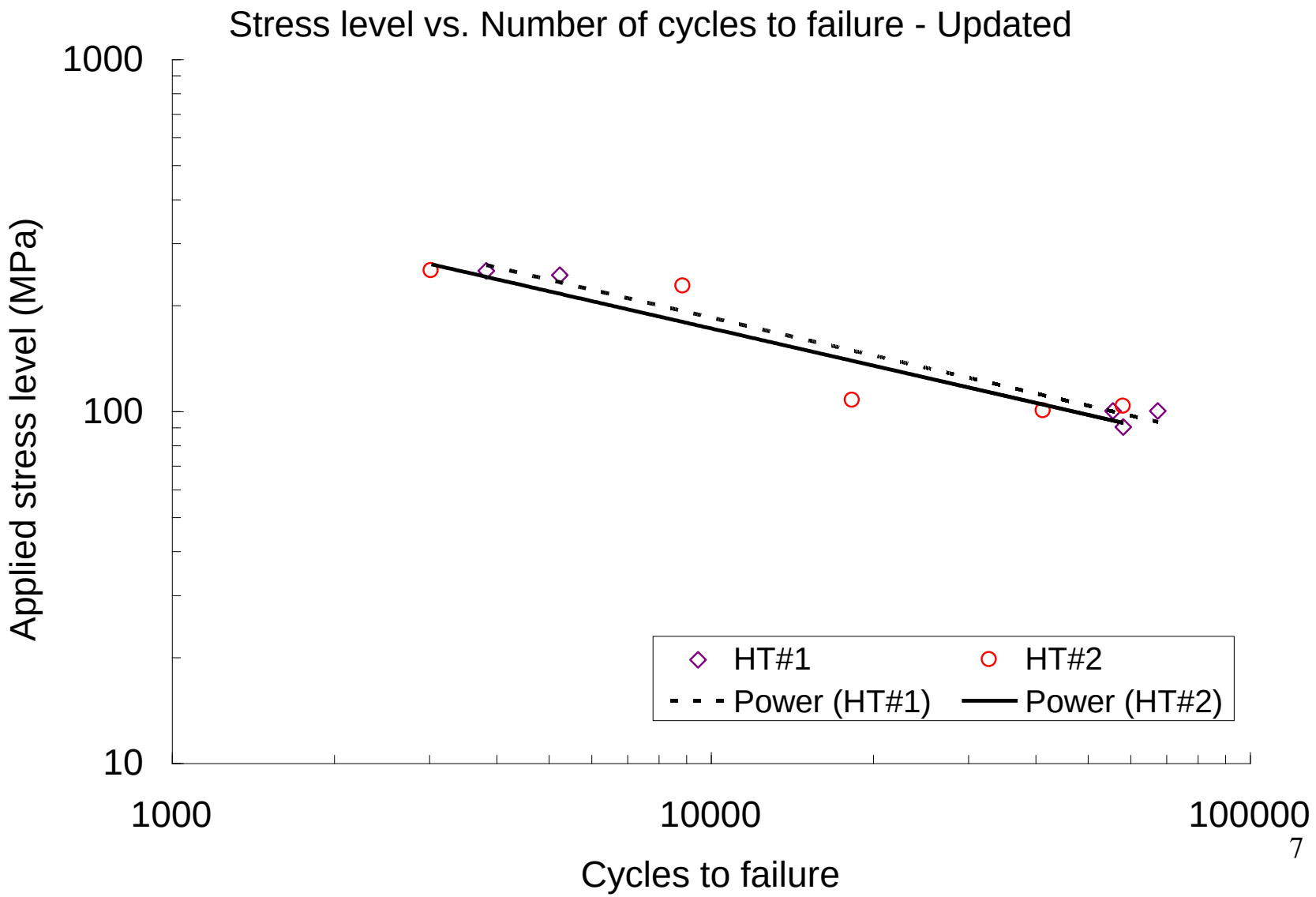
HT2 1 hr @ 850°C, 20 hrs @ 450°C							
Specimen number	**Thickness (mils)**	**Applied stress (MPa)**	**Cycles to failure Nf**	**Recoverable strain @ 1/2 Nf**	**Plastic strain @ 1/2 Nf**	**Recoverable strain @ Nf**	**Plastic strain @ Nf**
4	**5**	107	18338	0.0067	0.01406	0.00734	0.01926
5	**5**	103	58341 (run out)	0.00495	0.01676	0.00425	0.01901
7	**5**	250	3035	0.01123	0.00956	0.01063	0.01669
6	**10**	226	8897	0.00955	0.01154	0.00895	0.02059
9	**10**	100	41463	0.00384	0.01581	0.00424	0.02473
10	**10**	250	*creep like behavior - slip in grips*				
3	**15**	142	*creep like behavior - slip in grips*				
1	*Damaged during preliminary testing*						
2	*Not applicable for isobaric uniaxial fatigue testing - irregular cross section with major notches*						
8	*MTS tested*						

Table 2 is ordered according to increasing applied stress level

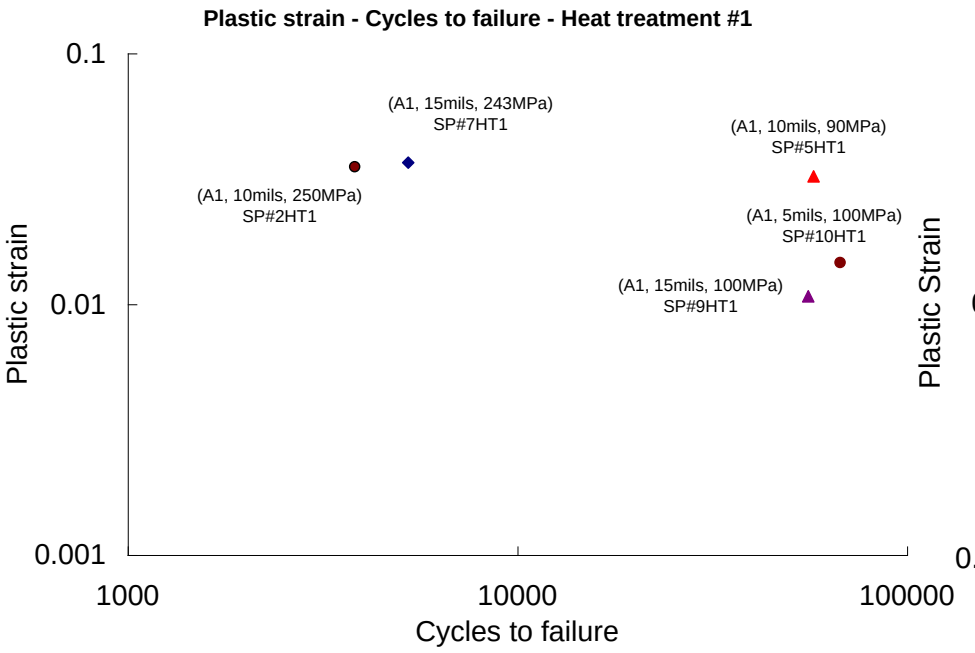
HT2 1 hr @ 850°C, 20 hrs @ 450°C							
Specimen number	**Thickness (mils)**	**Applied stress (MPa)**	**Cycles to failure Nf**	**Recoverable strain @ 1/2 Nf**	**Plastic strain @ 1/2 Nf**	**Recoverable strain @ Nf**	**Plastic strain @ Nf**
9	10	**100**	41463	0.00384	0.01581	0.00424	0.02473
5	5	**103**	58341 (run out)	0.00495	0.01676	0.00425	0.01901
4	5	**107**	18338	0.0067	0.01406	0.00734	0.01926
3	15	**142**	*creep like behavior - slip in grips*				
6	10	**226**	8897	0.00955	0.01154	0.00895	0.02059
7	5	**250**	3035	0.01123	0.00956	0.01063	0.01669
10	10	**250**	*creep like behavior - slip in grips*				
1	*Damaged during preliminary testing*						
2	*Not applicable for isobaric uniaxial fatigue testing - irregular cross section with major notches*						
8	*MTS tested*						

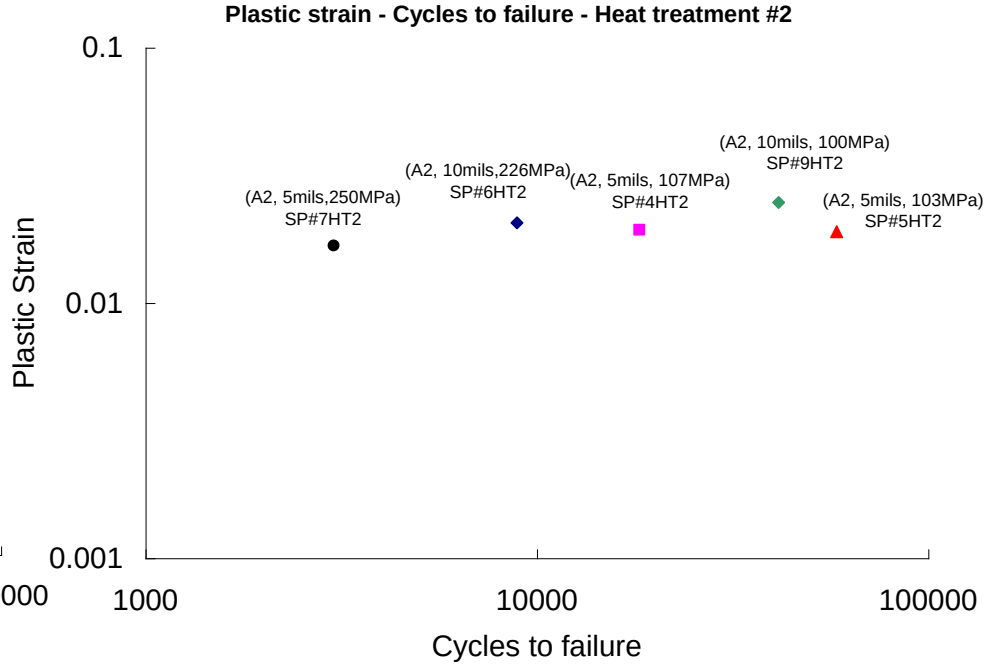
Remarks: Specimen #7 HT2 has a relatively small amount of accumulated plastic strain compared to the rest of the specimens

Stress – life updated



Plastic strain at failure - Updated





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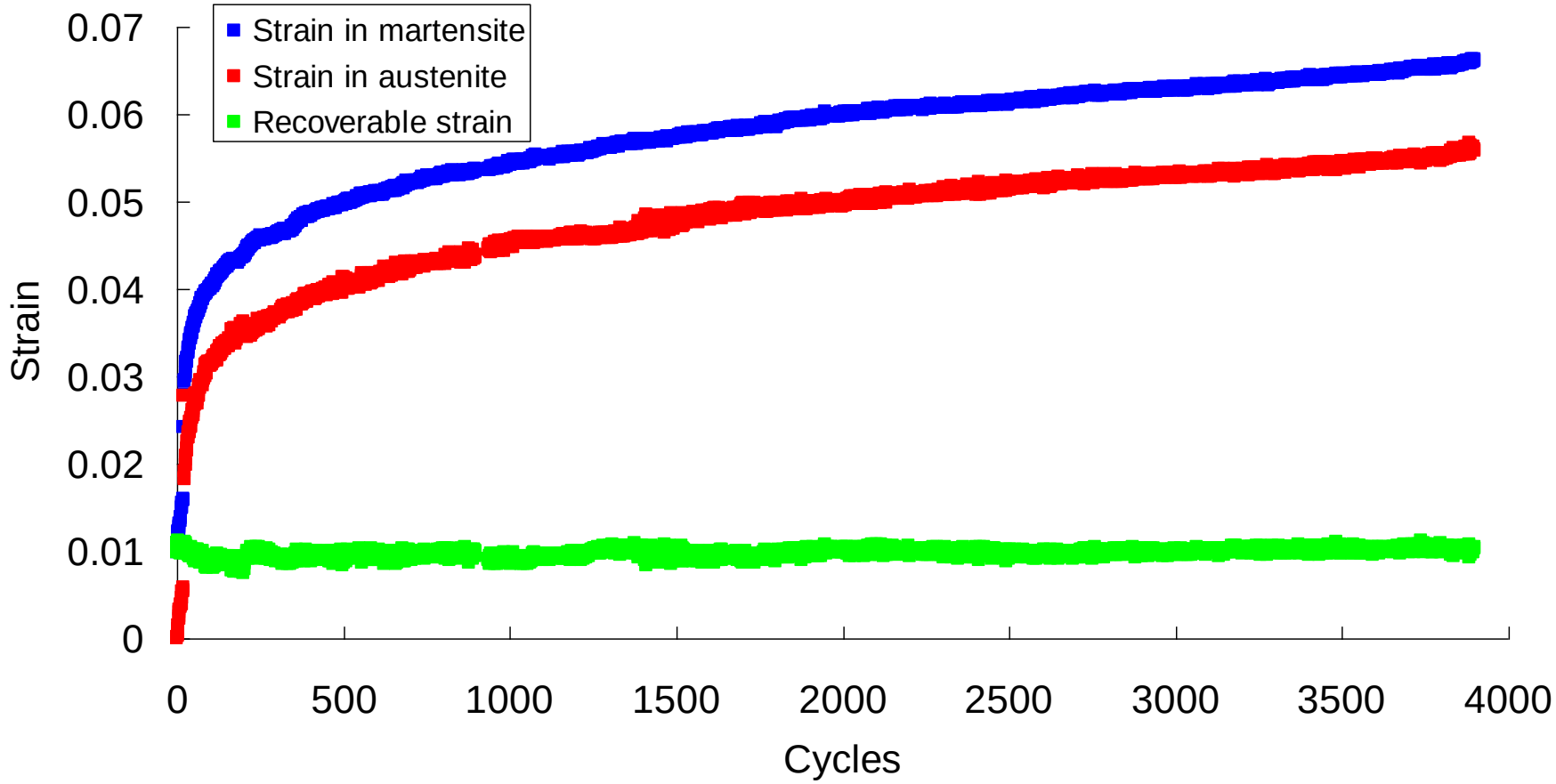
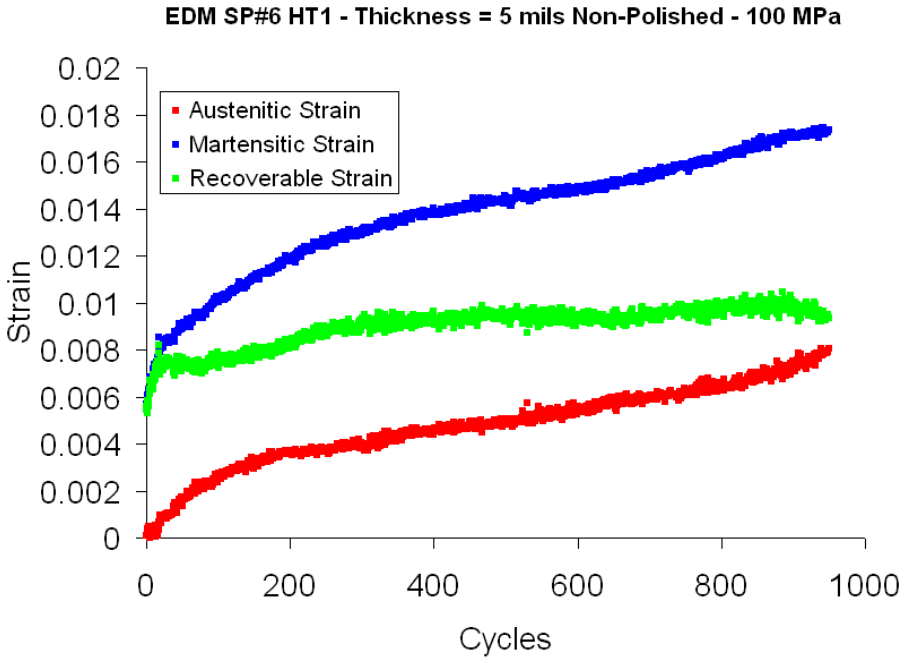
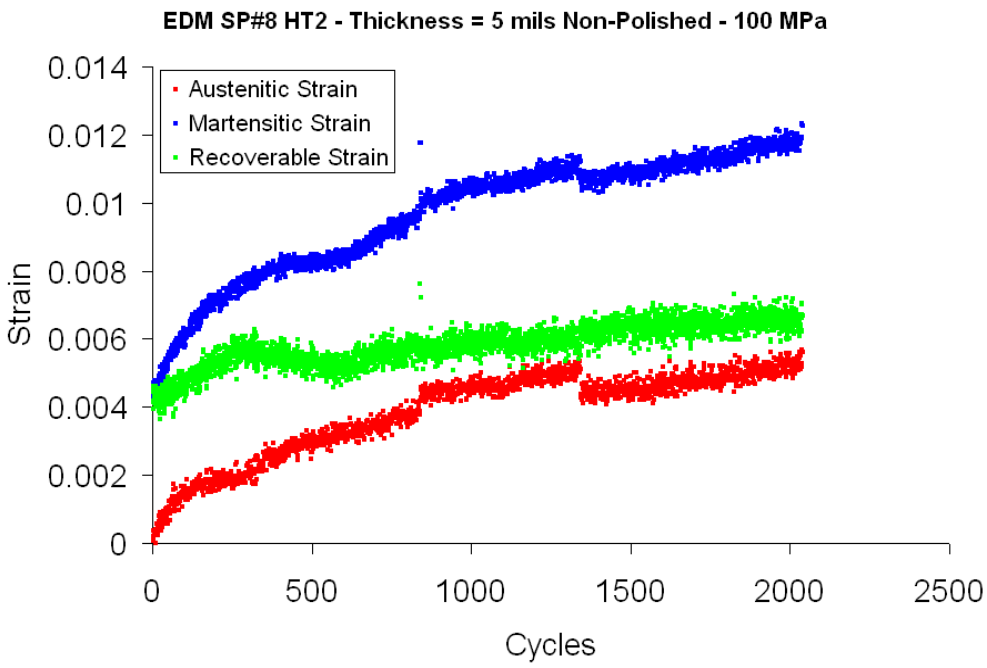
Presentation of first results

EDM processed SMA strips

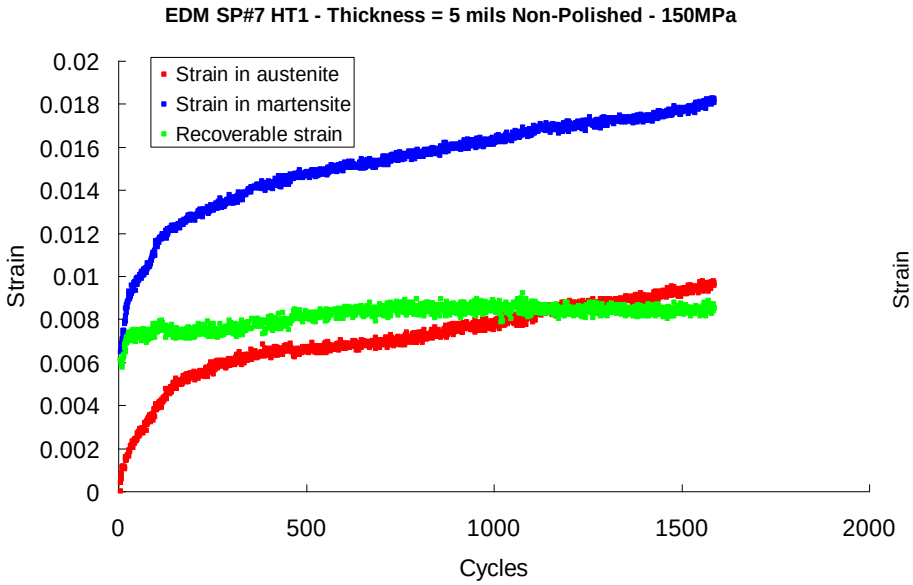

EDM SP#1 HT1 - Thickness = 15 mils Non-Polished - 250MPa
Strain in martensite
Strain in austenite
Recoverable strain
Strain
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
500
1000
1500
2000
2500
3000
3500
4000
Cycles

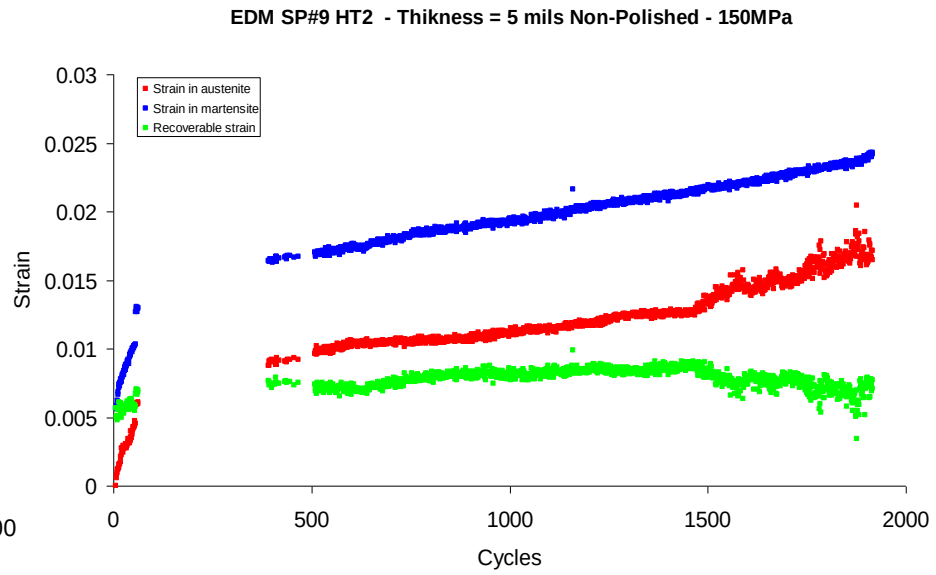
5 mils thick EDM Specimens under 100 MPa constant stress.





5 mils thick EDM Specimens under 150 MPa constant stress.





Stain vs. Life of EDM specimens compared to Strain vs. Life of water jet specimens for thickness = 5 mils

- EDM Specimens
  - 100 MPa
    - HT A1: 949 cycles
    - HT A2: 2039 cycles
  - 150 MPa
    - HT A1: 1588 cycles
    - HT A2: 1917 cycles
- Water Jet Specimens
  - 100 MPa
    - HT A1: 67571 cycles
    - HT A2: 18338 cycles
  - 150 MPa
    - HT A1: 6896 cycles (200 MPa)
    - HT A2: 58341 cycles (103MPa)

Influence of environment during heat treatment on fracture surfaces

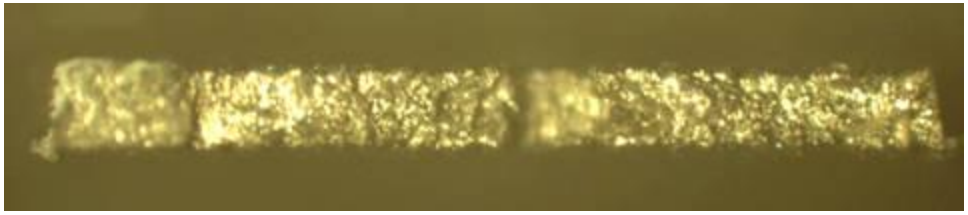
- Recall initial optical microstructural analysis for identification of possible failure modes

- Presentation of EDM processed specimens fracture surfaces to assess existence of oxide layer

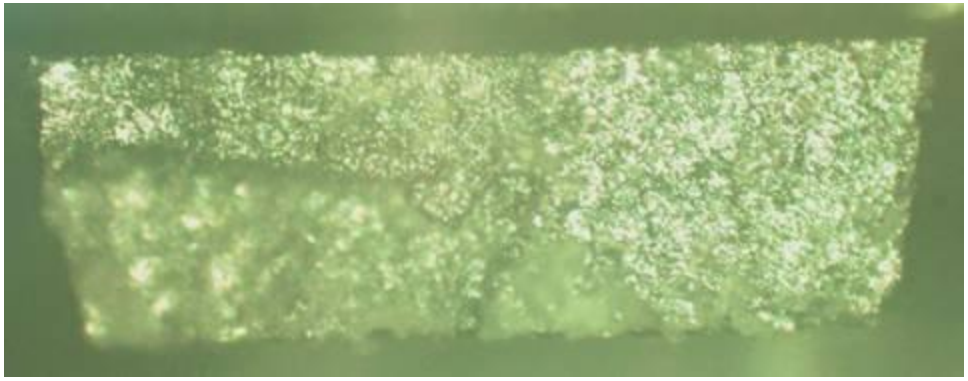
- Conclusions on the presence of consequential oxide layer

Failure of specimens - water jet

- Influence of thickness under identical stress level



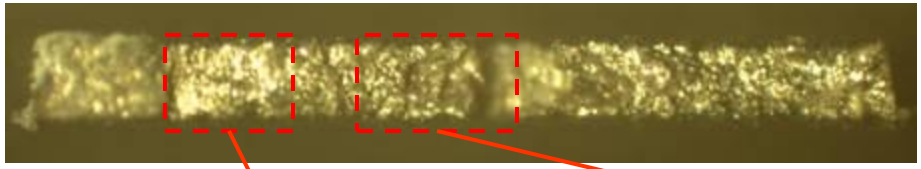
SP#3 HT1 – thickness = 5 mils



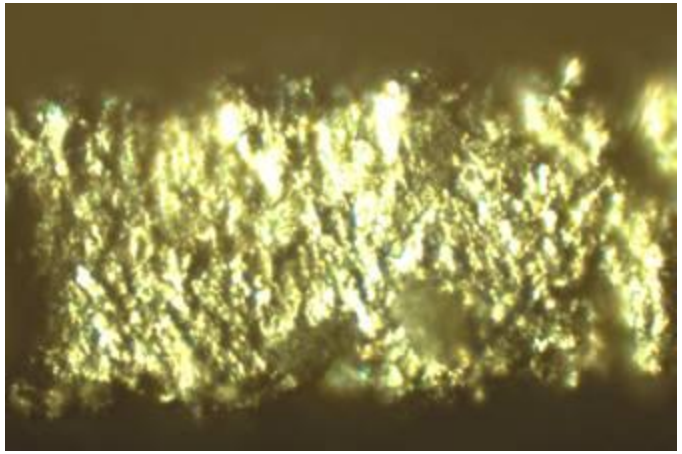
SP#7 HT1 – thickness = 15 mils

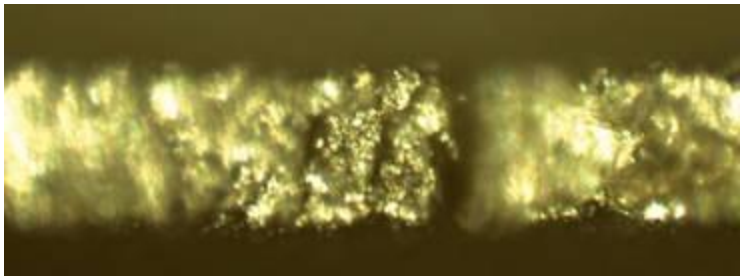
- Influence of thickness can be seen as cracks are generated in the transverse direction of SP#3 HT1 where PS#7 HT1 displays more of a bulk behavior
- Different failure behavior from thickness 5 mils to 15 mils

Failure of specimens



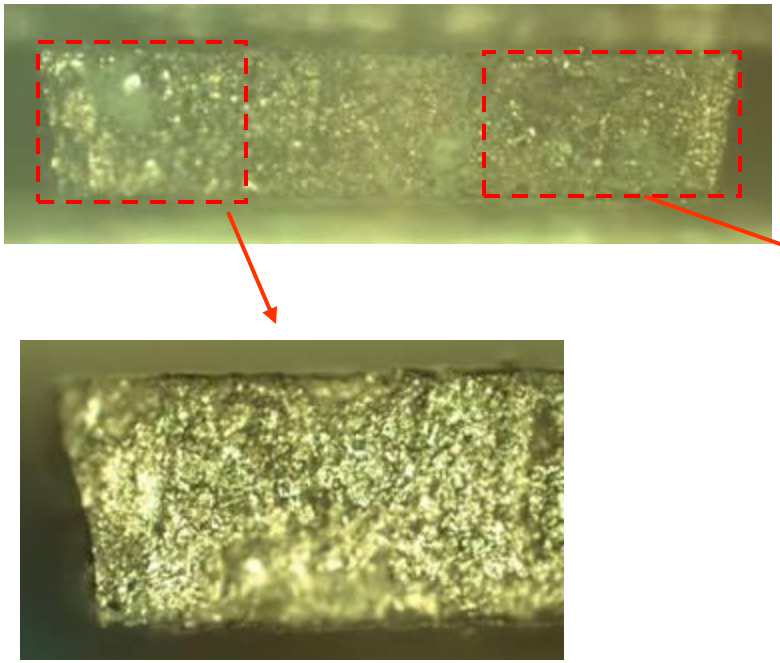
SP#3 HT1 – thickness = 5 mils



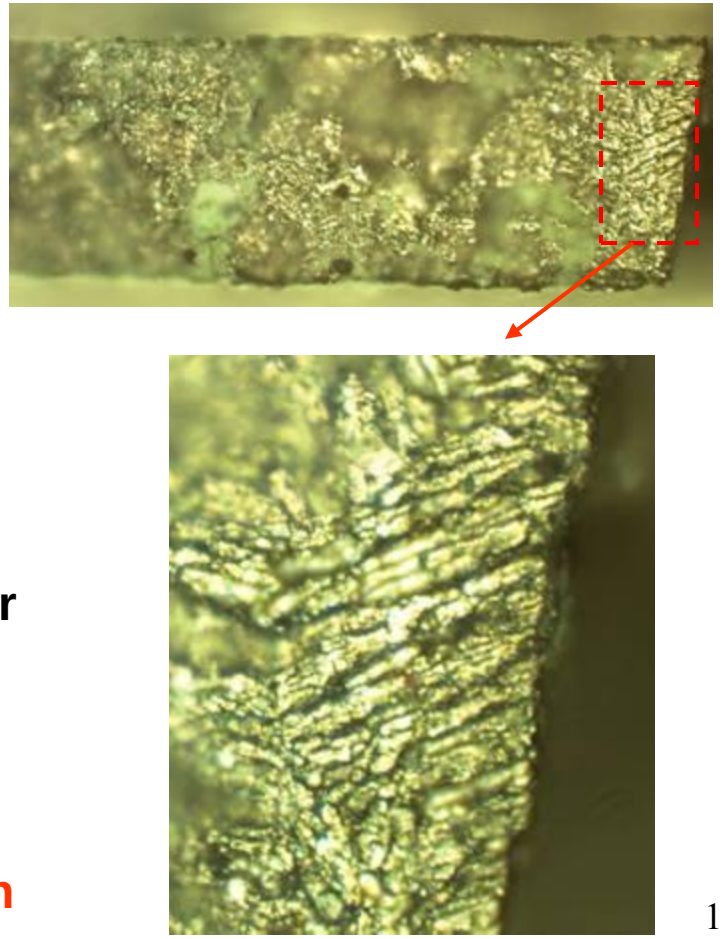


- **Transverse cracks and transverse tear up – strong dependency on the width to height ratio**
- **Propagation of fatigue lines in a transverse pattern**

Failure of specimens



SP#6 HT2 – thickness = 10 mils



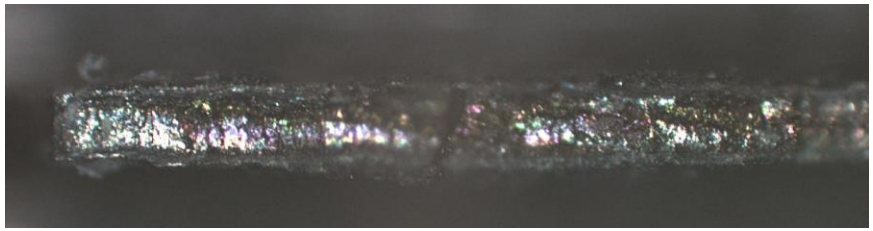
- **Thicker specimens display bulk behavior with multi-axial fatigue damage and propagation**

- **Notice the non-existence of contrasted surface layer: heat treatment performed in vacuum**

Failure of specimens - EDM

- EDM specimens failing too early under 100MPa and 150MPa applied stress led to analysis of oxide layer due to heat treatment performed in air vs. in vacuum

Nf (HT in air, 100 -150 MPa) < 2000 cycles	↔	Nf (HT in vacuum, 100 – 150 MPa) ≈ 50000 cycles

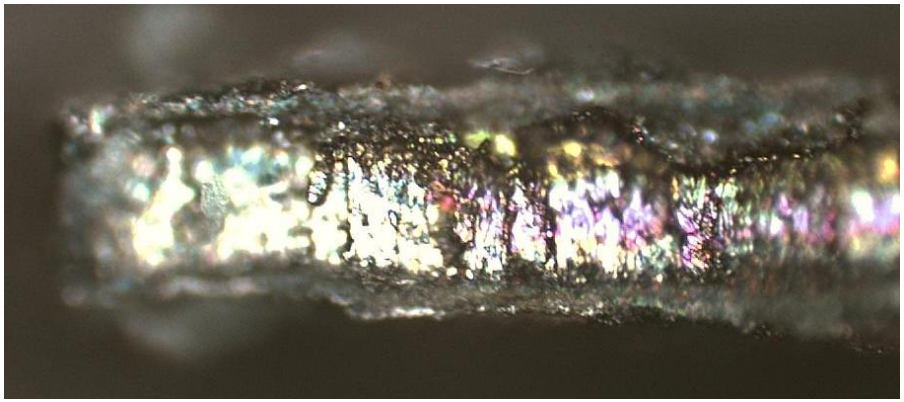


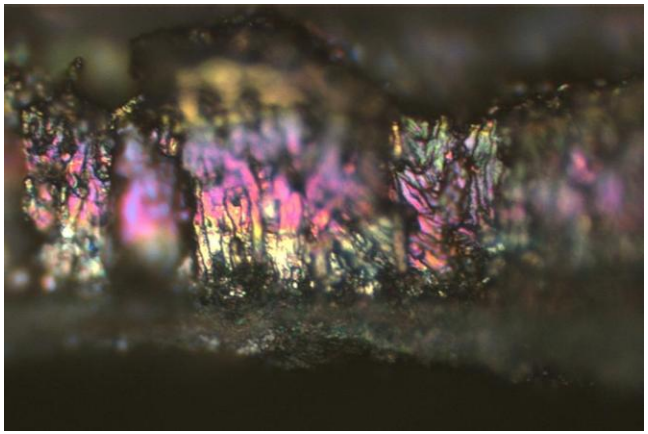
SP#6 HT1 – thickness = 5 mils

SP#8 HT2 – thickness = 5 mils

Failure of specimens - EDM

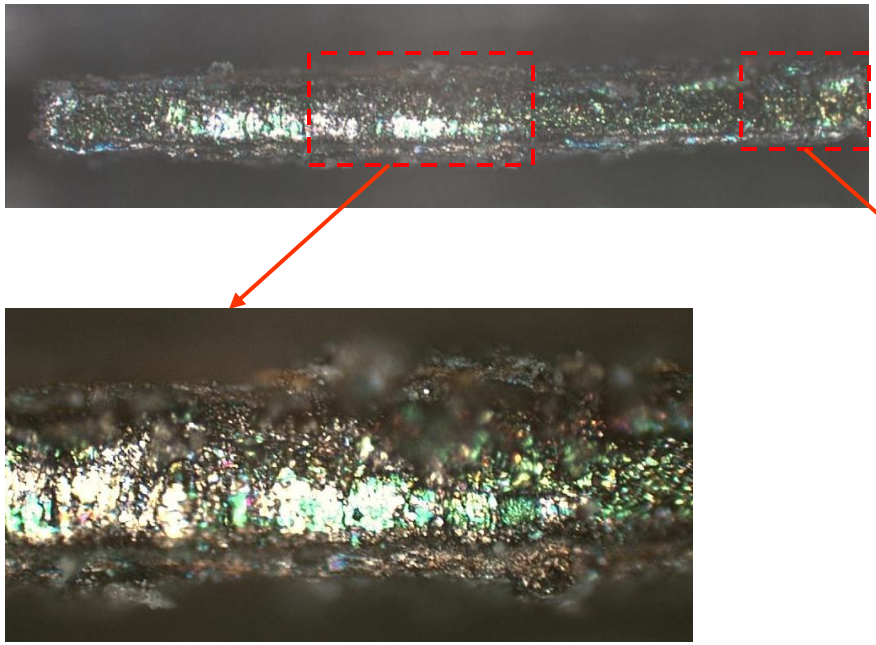
SP#6 HT1 – thickness = 5 mils



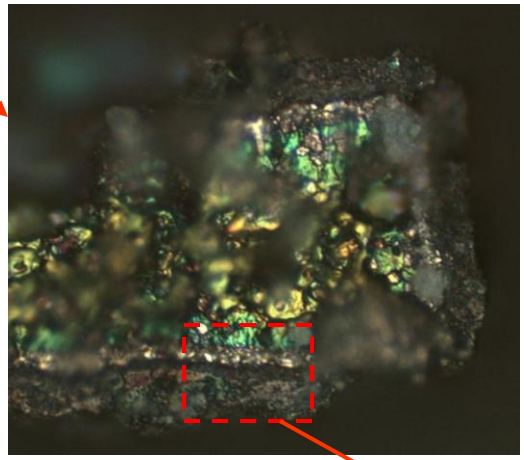


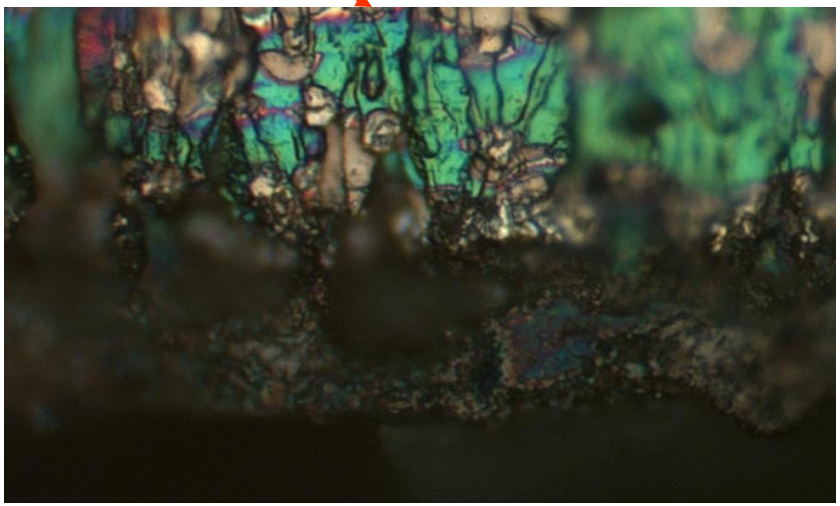
- Similar transverse fatigue lines with crack propagation along the same direction
- Significant contrasted surface layer on the specimens: initial oxide layer formed upon heat treatment. Interface is clear and cracks can be identified

Failure of specimens - EDM



SP#8 HT2 – thickness = 5 mils





- Specimens with minimum thickness (5 mils), failed very early due to a significant oxide layer contributing to crack initiation and to embrittlement

Recommendations for further testing

- Selection of heat treatment for better control over fatigue experiments and to enhance time to achieve fatigue testing: **Heat Treatment 2**

- Stress range to perform fatigue testing needs to be adjusted to **100 – 150 – 250 MPa**

- Selection of ideal thickness for best material response is to be **15 mils** (20 mils if stress range reduced to 100 – 150 – 200 MPa)

- Modification of actual test matrix to account for suggested modifications

Latest test matrix

Chosen Heat Treatment	A2*	
Chosen Specimen Thickness	.015 in.	(.381 mm)

Test Matrix		
Stress Applied (MPa)	Polished Specimens	Non-Polished Specimens
100	3	3
150	3	3
250	3	3

*HT #2 = 1 hr 850 C, furnace cool, 20 hrs 450 C, water quench.

Currently **18** new specimens will be needed:
9 polished
9 non-polished