Effects of Post-Drawing Surface Heat Treatments on the Strength and Torsional Ductility of High Strength Steel Wire

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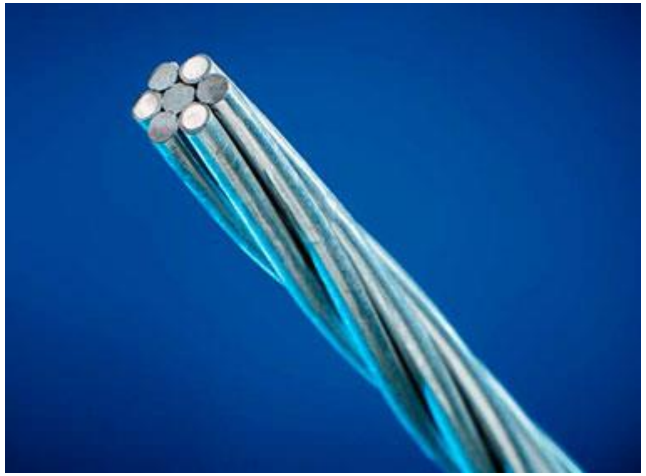
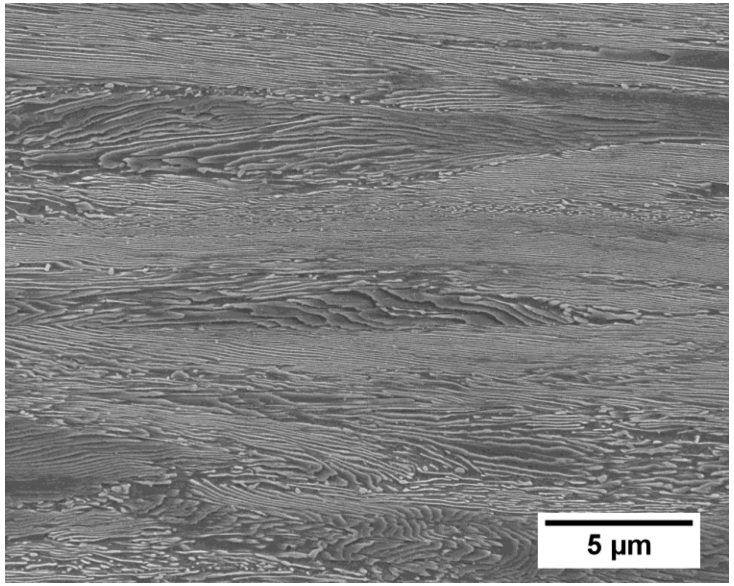
Industrial Relevance

- Used in bridge cable, mooring cable, hoisting rope, etc.
- Need to have high strengths, but also good ductility for downstream processability
- Multiple strands are twisted together to increase breaking loads of these cables
- Galvanized coating applied for corrosion resistance



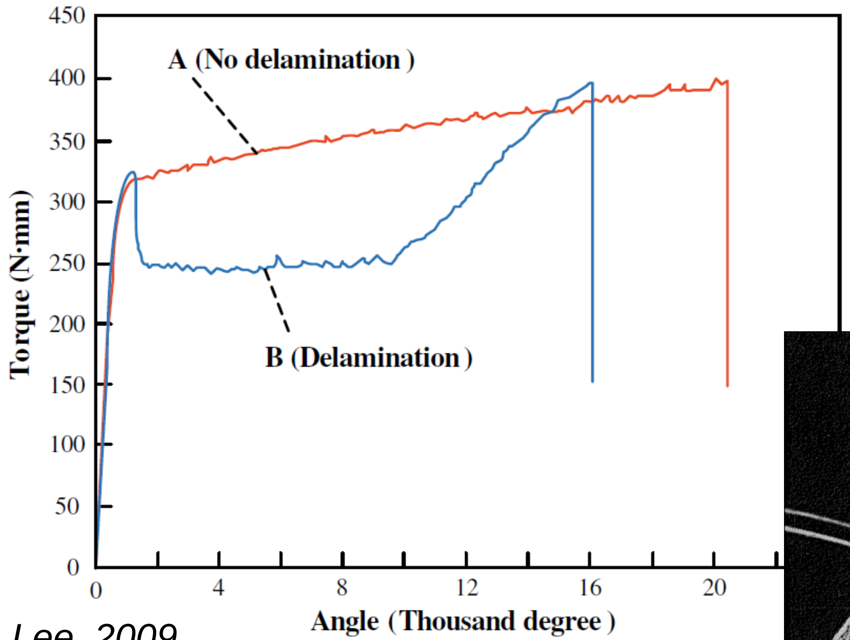
www.bekaert.com



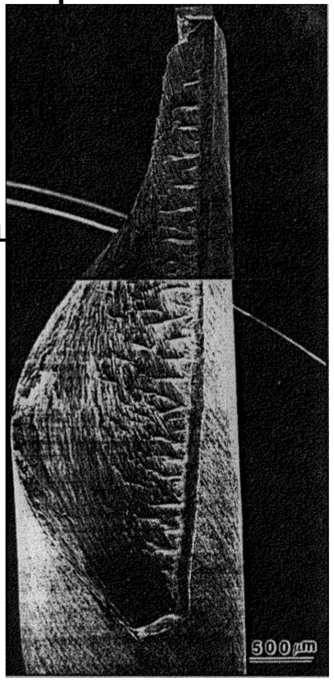
Torsional Ductility – Delamination

- Defined as the longitudinal splitting of a wire due to low ductility

- Influenced by:
  - Interlamellar spacing
  - Texture
  - Inclusion content
  - Residual stress
  - Cementite dissolutions
  - Strength level



Lee, 2009.



Su, 2000.

Materials Selection

wt pct	C	Mn	Si	Ni	Cr	Mo	Ti	Al	N	S	P	Cu
LC-LSi (0.92 C-0.2 Si)	0.93	0.33	0.22	0.016	0.23	0.005	-	0.001	0.005	0.004	0.006	0.014
HC-LSi (1.0 C-0.2 Si)	1.01	0.33	0.22	0.016	0.23	0.004	-	0.001	0.003	0.004	0.008	0.011
LC-HSi (0.92 C-1.2 Si)	0.94	0.32	1.24	0.013	0.23	0.004	-	0.001	0.004	0.004	0.005	0.012

Materials provided by Bekaert

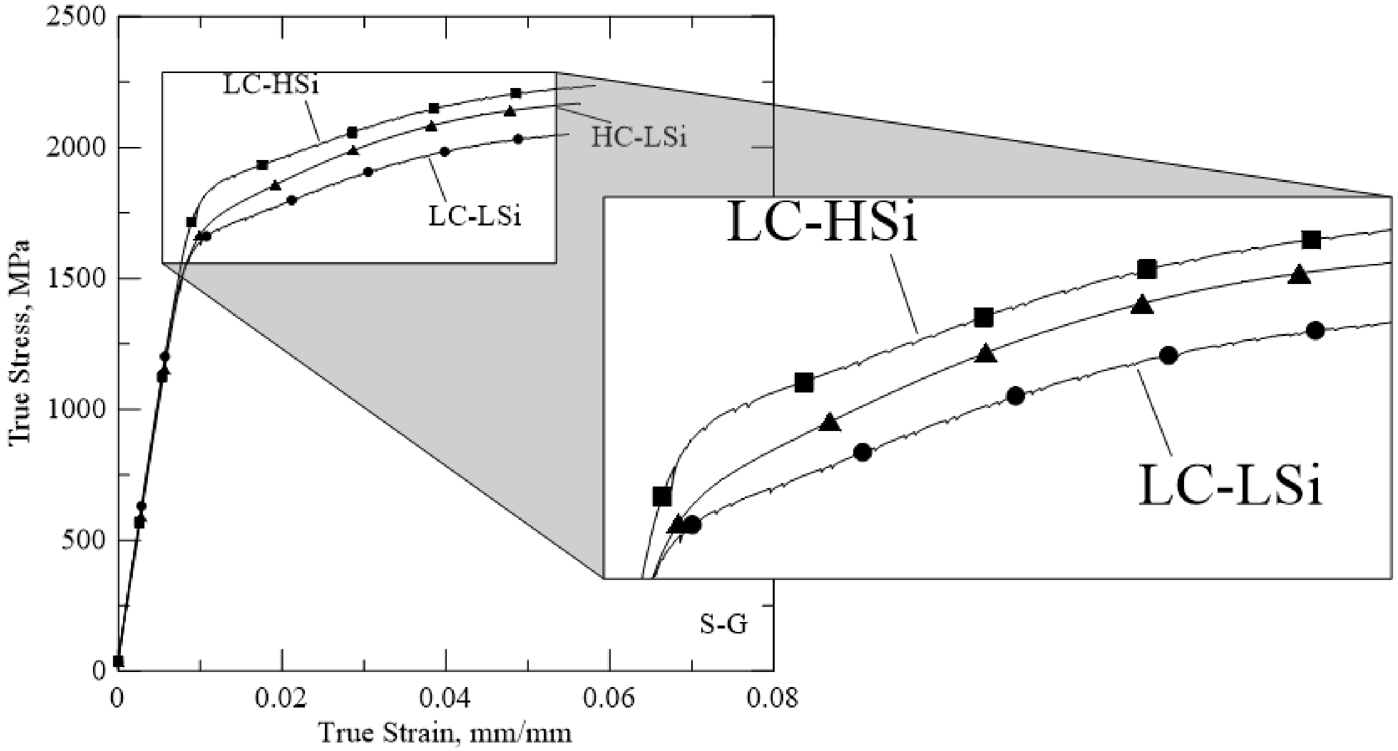
Wire Rod	0.92 C-0.2 Si (13 mm), 1.0 C-0.2 Si (13 mm), 0.92 C-1.2 Si (12.5 mm)			
Heat Treatment	Stelmor		Pb Patenting	
Drawing Steps	Direct drawing from wire rod to final diameter (5.3mm)		Predraw to 12.5mm, Pb patent, final drawing to final diameter (5.3mm)	
Surface Finish	Bright (As-drawn)	Hot-dip Galvanized	Bright (As-drawn)	Hot-dip Galvanized

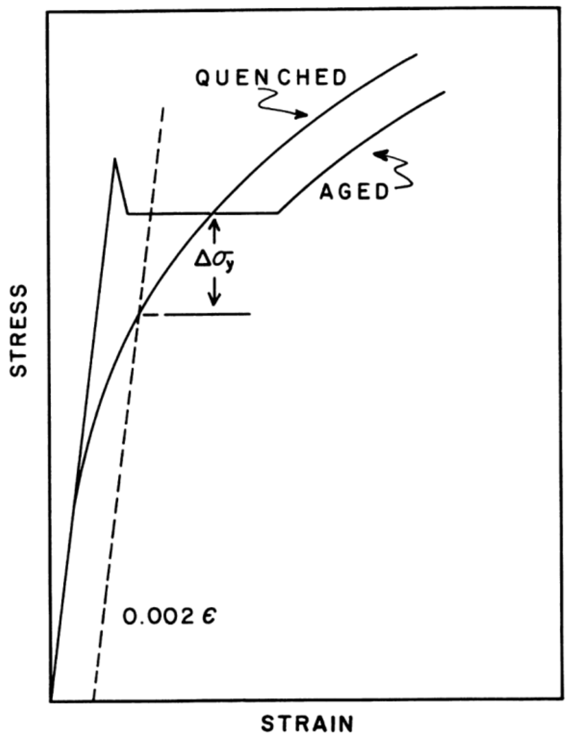
Mechanical Testing Nomenclature

Term	Abbreviation
Low Carbon (0.92 wt pct)	LC
High Carbon (1.0 wt pct)	HC
Low Silicon (0.2 wt pct)	LSi
High Silicon (1.2 wt pct)	HSi
Stelmor Cooled	S
Lead Patented	P
As-Drawn	AD
Galvanized	G

LC-HSi-S-AD =
low carbon, high silicon, Stelmor cooled, as-drawn

Preliminary Observations: True Stress-Strain





Krauss, 2005.

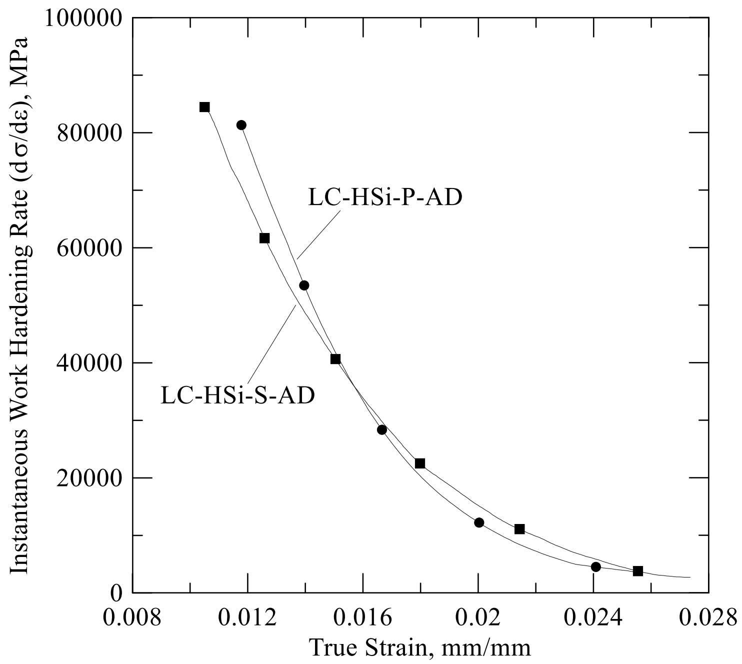
- Variation in plastic deformation behavior reminiscent of yield point elongation phenomena

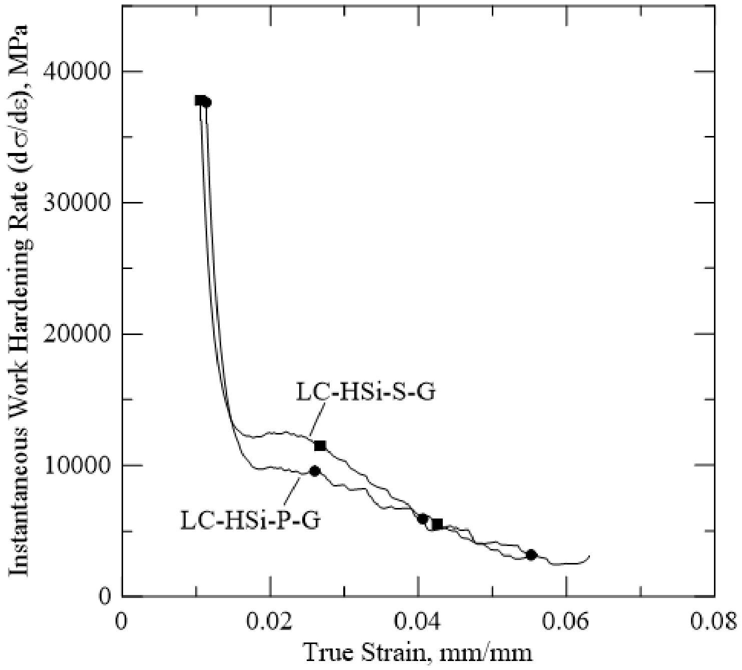
Does this low strain phenomena correlate to delamination in torsion?

Preliminary Observations: Inst. Work Hardening Rate (IWHR)

- As-drawn wire IWHR significantly higher in magnitude at low strains
- As-drawn wires (ductile failure) exhibit continuous decrease in IWHR

- Galvanized wires (delamination) experience abrupt change in IWHR
- Level off at low strains, then slow decrease

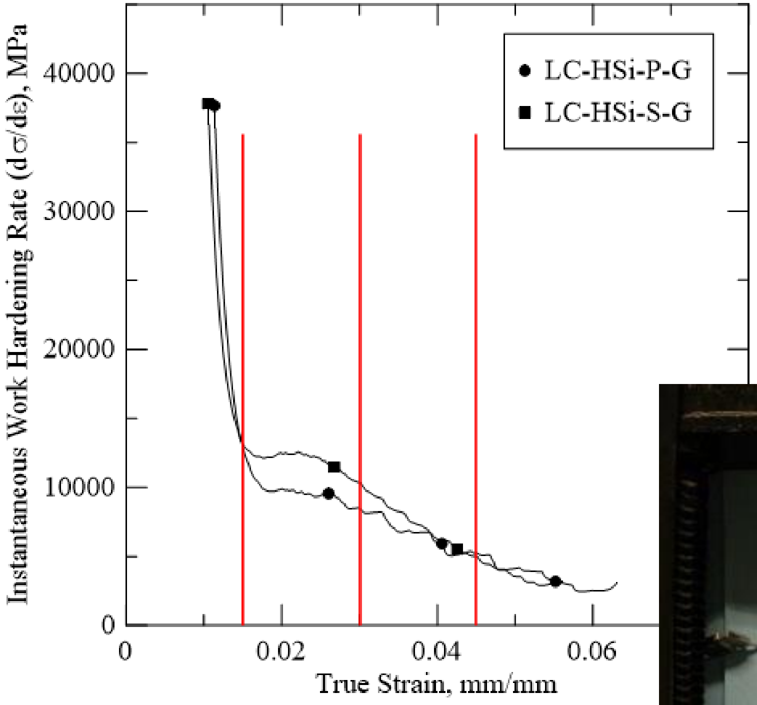




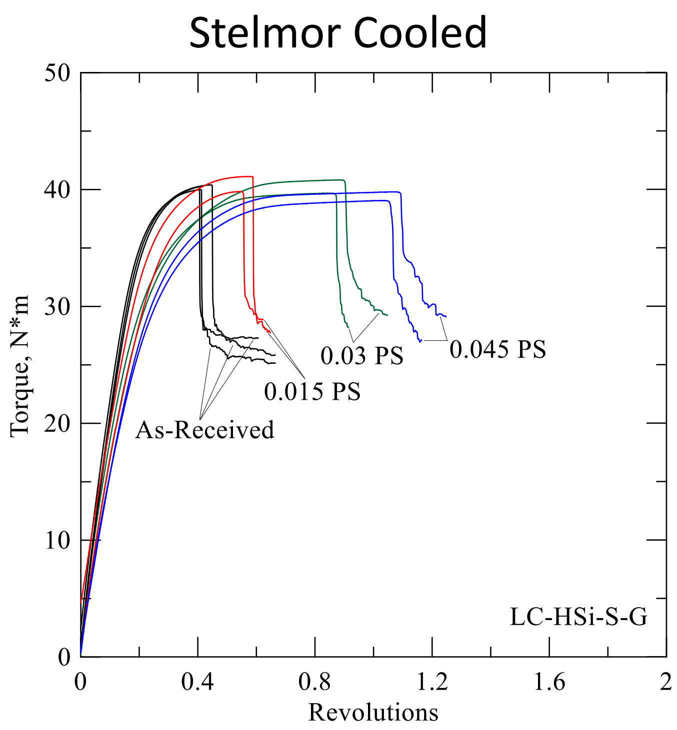
Study Objective and Experimental Design

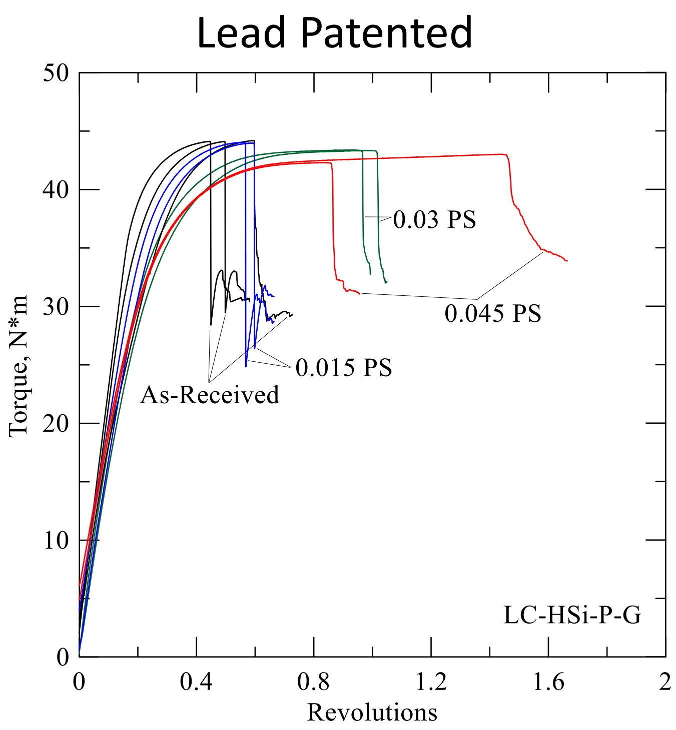
Does mechanical deformation affect torsional performance?

- Three prestrain levels selected: 1.5, 3, and 4.5 pct
- Compared Stelmor cooled to lead patented wire conditions
- Torsion tested wires after prestrained



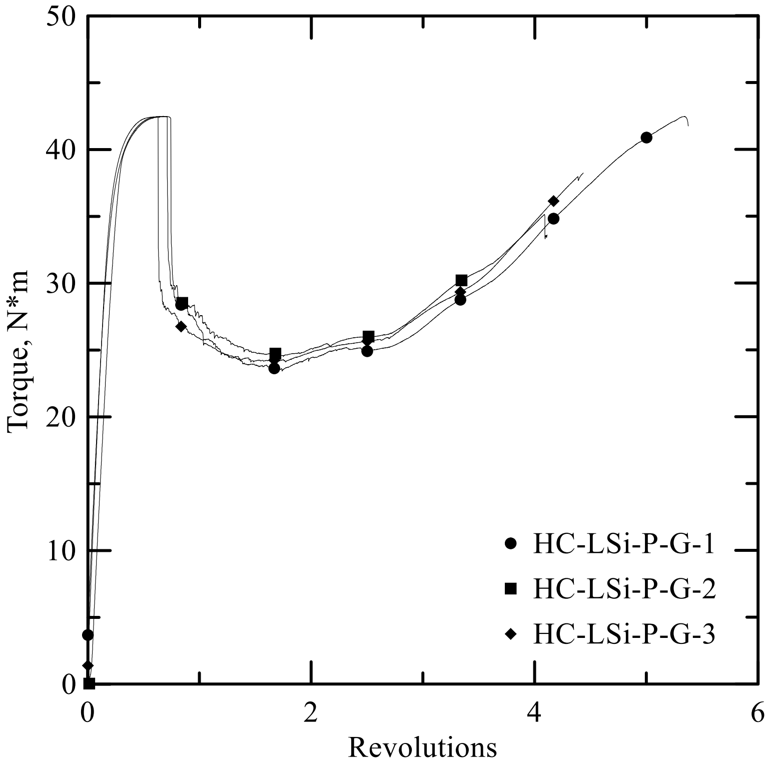
Torque-Twist Curve Characteristics





- Delamination failure not avoided
- Increasing prestrain:
  - Increased torsional ductility for both conditions
  - Reduced slope in low strain regime
  - Increased stress saturation after yielding

Delamination Property Calculations



Shear Strain

$$\boldsymbol{\gamma = \frac{r}{L}\theta}$$

r = wire radius

L = gage length

θ = angle of twist

Shear Stress

$$\boldsymbol{\tau = \frac{1}{2\pi r^3}\left(\theta' \frac{dM_T}{d\theta'} + 3M_T\right)}$$

θ’ = θ/L

M_T = torque

Nadai, 1950.

Delamination Property Comparisons

- With increasing prestrain:
  - Surface shear strain at delamination increased significantly
  - Surface shear stress at delamination moderately decreased

Magnitude of change in properties nearly identical for both wire conditions

	Average Surface Shear Stress to Delamination	Change in As-Received Surface Shear Stress to Delamination	Average Surface Shear Strain to Delamination	Change in As-Received Surface Shear Strain to Delamination
As-Received	996	-	0.054	-
0.015 Prestrain	949	-46	0.072	0.019
0.03 Prestrain	909	-87	0.112	0.058
0.045 Prestrain	881	-114	0.136	0.082

	Average Surface Shear Stress to Delamination	Change in As-Received Surface Shear Stress to Delamination	Average Surface Shear Strain to Delamination	Change in As-Received Surface Shear Strain to Delamination
As-Received	1104	-	0.065	-
0.015 Prestrain	1062	-42	0.073	0.008
0.03 Prestrain	1012	-92	0.120	0.055
0.045 Prestrain	1023	-81	0.144	0.079

Conclusions

- Torsional performance improved by mechanical deformation through prestrain
- Processing path (Stelmor cooled or lead patented) did not vary the effect of prestraining
- Potential mechanisms that lead to improved torsional ductility:
  - Internal stresses and dislocation density change during deformation
  - Void quantity or morphology are modified by prestrain

Future work

- Expand to other wire compositions
- Explore the evolution of void quantity and morphology through prestraining
- Quantify change in stress state caused by prestrain deformation
- Run industrial trials of skin passes on wires and compare to prestrain results