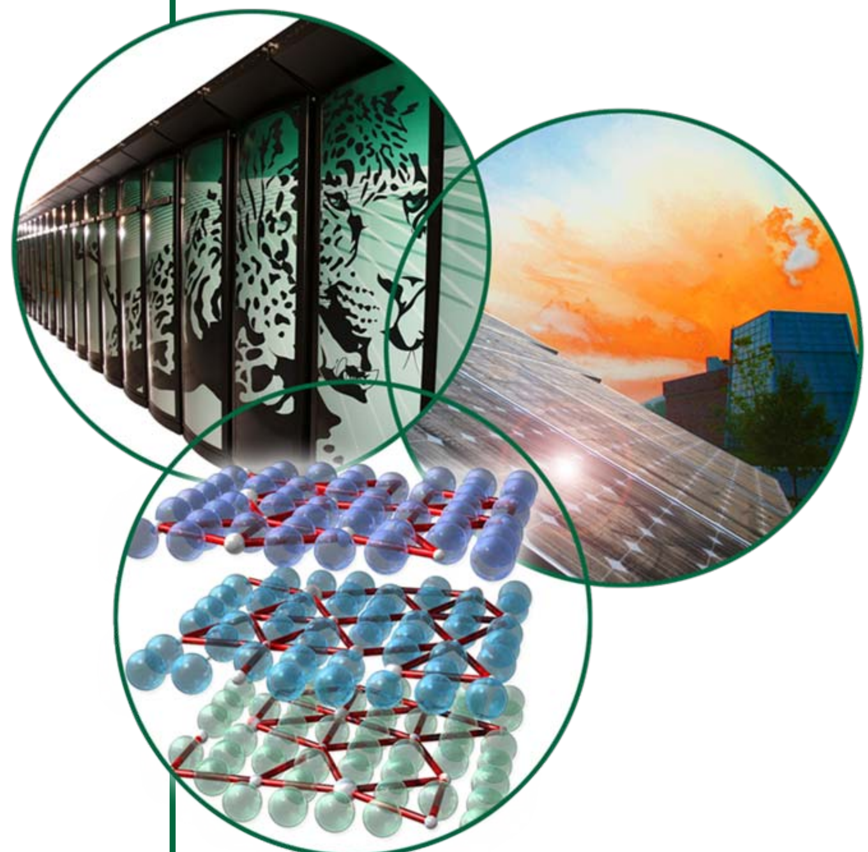
Project ID: Imp_03_hubbard

Residual Stresses for Structural Analysis and Fatigue Life Prediction in Vehicle Components: Success stories from the High Temperature Materials Laboratory (HTML) User Program

DOE 2009 Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

May 21, 2009



Dr. Camden Hubbard, ORNL

Sponsored by
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The HTML User Program - Background

The HTML is a National User Facility that supports the missions of DOE, EERE and the Vehicle Technologies Program in particular, by working with industry, universities and other national laboratories to develop energy efficient technologies that will enable the U.S. to use less petroleum. The HTML is organized into six user centers, which are clusters of highly skilled staff and sophisticated, often one-of-a-kind instruments for materials characterization.

Access to the HTML is provided through the HTML User Program proposal process. Research proposals are reviewed by a committee and approved based on scientific merit, relevance of the proposed research to the mission of DOE's Vehicle Technologies Program, and feasibility. Research is completed within 24 months and normally involves one or more user visits to the HTML.

Both nonproprietary and proprietary research is conducted within the HTML User Program. There are generally no charges for nonproprietary research projects, and users conducting nonproprietary research must agree to submit research results for publication in the open, refereed literature. For proprietary research, the user owns the research data and all costs at the HTML are paid by the user based on DOE guidelines for ORNL costs. A nonproprietary project is complete when the results are published in the open literature and/or presented at a professional conference.

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The HTML User Program – FY2008 Activity

During FY2008, the HTML User Program managed 76 user projects from 53 different organizations.

The FY2008 budget for the HTML was $6,072,283 and was allocated as follows:

- $1,567,500 for capital equipment purchases
- $3,879,483 to support staff participation in user projects
- $626,000 for the operation of the user program

Users cost-share user projects through:

1) their direct involvement with HTML staff members during the development of the user project;
2) funding their travel to the HTML to perform research;
3) costs of materials provided by the user or the research performed prior to the user project;
4) their subsequent collaboration with HTML staff members to analyze the data and publish the results.

The HTML also supports the education and preparation of a new generation of scientists and engineers.

During FY2008, students and professors from 32 universities participated in the HTML User Program. Four of those students received their Ph.D. degree in FY2008 based in part on research performed through the HTML User Program.

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Metalsa Roanoke, Inc.

"Measurement of residual stress in the edge of the hole cutting by several processes in the railsides for truck frames"

Timeline

- Start date: 10/1/07
- End research: 4/30/08
- Publish results: ongoing
- % complete: 90%

Barriers

- Light weight materials for heavy vehicles
- Materials evaluation for alternative materials
- Process evaluation

Budget

- Included in the user center allocations from the annual budget of the HTML User Program; users cost-share as previously noted.

Collaborators

- Users:
  Sean Fleming
  Joaquin del Prado
- HTML Staff:
  Cameron Hubbard

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Relevance to the VT Program

- The Vehicle Technologies Program supports the HTML User Program and provides an annual budget to address a wide range of materials-related issues in ground transportation systems arising from R&D needs in U.S. industry.
- The user project described in this poster presentation and those listed in the appendix are relevant to the mission of the Vehicle Technologies Program, because they address the goals of material and manufacturing technologies for high volume production vehicles that enable/support the simultaneous attainment of reduction in the weight of vehicle structure and subsystems and affordability, and increased use of recyclable/renewable materials.

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User Project with Metalsa Roanoke

Experimental Plan: Study near-hole residual stress & fatigue crack growth for typical CV siderail hole-making processes applied to heat-treated MET1123 steel and 120XF ultra high strength low alloy steel

Research Objectives:

- Evaluate industry standard heat-treated and alternative high strength low alloy steel
- Assess impact of common hole-making processes on commercial vehicle siderail durability, specifically the residual stresses and crack growth properties

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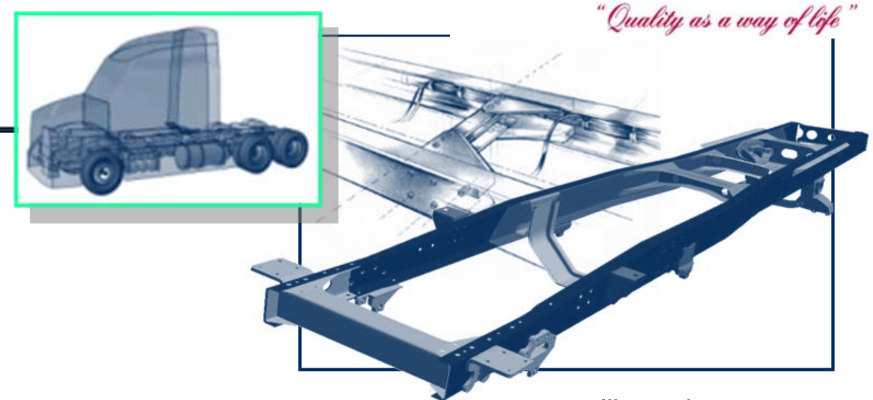
User Project with Metalsa Roanoke

DOE and Industry Drivers



Illustrations courtesy of Metalsa Roanoke.

Whats?

- Substantial Payload Improvement, e.g. 15%-25% chassis weight reduction
- Maintain Performance
- Improved Fuel Usage

How?

- Better Utilization of Chassis Materials – Steel, Aluminum
- Development of higher strength steel grades
- Better knowledge of Process Techniques on Chassis Components
- Optimized Chassis / Frames with high level of confidence

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User Project with Metalsa Roanoke

Milestones

Month/Year	Milestone
October 2007	Submit HTML User Proposal
December 2007	Select best specimens for production and all measurements for the combined stress and fatigue crack studies and produce samples
April 2008	Complete neutron residual stress mapping measurements at HTML
September 2008	Complete microstructure, properties and fatigue crack studies at Metalsa
October 2008	Complete analysis, presentation at SAE International Conference
June 2009	Submit paper for publication

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User Project with Metalsa Roanoke
Approach

- Design experiment and approach (Metalsa, ORNL-HTML)
- Develop baseline materials properties (Metalsa)
  - Monotonic materials testing
  - Fatigue for strain life
- Hole making in MET1123 HT and 120XF HSLA (Metalsa)
  - Four common hole making processes selected for comparison
  - Punch, NC Drill, CO_2 Laser, O_2 Plasma
- Use neutron residual stress mapping method to map the near hole residual stresses within the multiple steel plates (ORNL-HTML, Metalsa)
- Conduct fatigue crack growth measurements (Metalsa)
- Prepare report, presentations and publications (Metalsa, ORNL-HTML)

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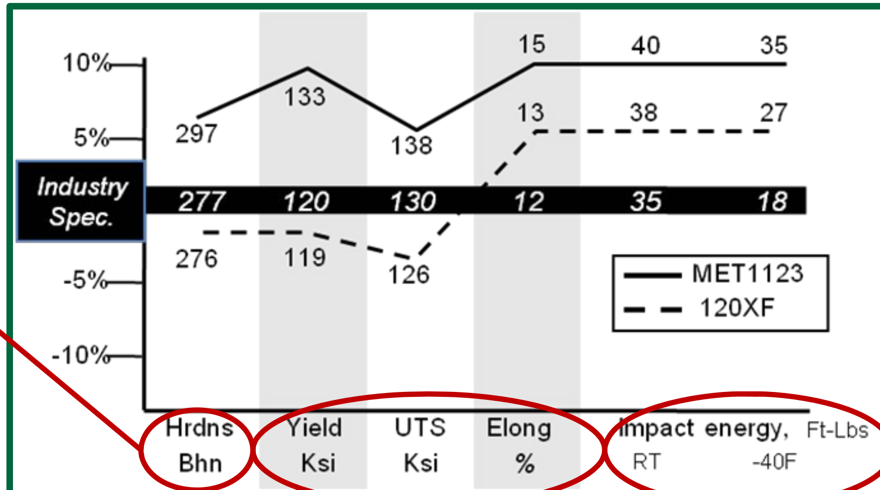
User Project with Metalsa Roanoke

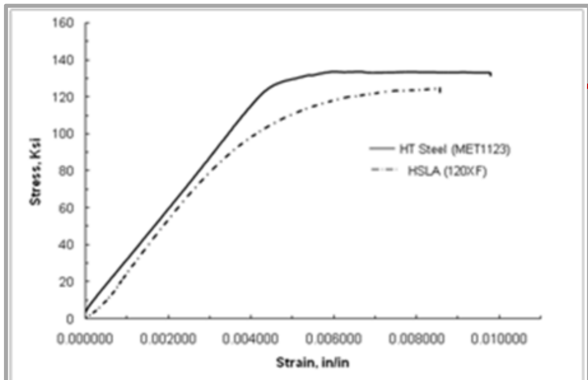
Materials Testing: monotonic (Metalsa)

Metalsa Roanoke
"Quality as a way of life"

MET1123 Specimen	Hardness, BHN	120XF Specimen	Hardness, BHN
HT-1	293	HSLA-1	285
HT-2	297	HSLA-2	271
HT-3	298	HSLA-3	265
HT-4	298	HSLA-4	262
HT-5	297	HSLA-5	285
HT-6	300	HSLA-6	285
AVG→	297	AVG→	276

Brinell Hardness (BHN) – ASTM E10-07.





***Stress-strain curves** for MET1123 (solid line) and 120XF (dotted line).*

Specimen	0.2% yield, ksi	UTS, ksi	Elong, %	RA, %
HT-1*	134.1	138.8	16	51
HT-2	135.2	138.4	15	57
HT-	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
AVG	[illegible]	[illegible]	[illegible]	[illegible]

Specimen	0.2% yield, ksi	UTS, ksi	Elong, %	RA, %
HSLA-1*	120.2	127.1	13	58
HSLA-2	117.1	124.7	13	60
HSLA-3	119.2	126.3	13	58
HSLA-4	119.7	126.5	13	57
HSLA-5	118.7	125.7	15	46
HSLA-6	119.5	125.2	13	58
AVG	119.1	125.9	13	56

Yield Strength, UTS, Elong, RA -ASTM E8-04

Specimen	Temp., F	Energy, ft-lbs	Mils Lat Exp	% Shear Frac.
HT-1	Room	40	35	40
HT-2	Room	42	49	40
HT-	[illegible]	[illegible]	[illegible]	[illegible]
AVG	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
HT-	[illegible]	[illegible]	[illegible]	[illegible]
AVG	[illegible]	[illegible]	[illegible]	[illegible]

Specimen	Temp., F	Energy, ft-lbs	Mils Lat Exp	% Shear Frac.
HSLA-1	Room	38	54	100
HSLA-2	Room	39	52	100
HSLA-3	Room	38	50	100
AVG	--	38	52	100
HSLA-4	-40F	26	33	100
HSLA-5	-40F	25	30	100
HSLA-6	-40F	29	33	100
AVG	--	27	32	100

***Charpy Impact**: RT & -40 – ASTM E23-07*

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User Project with Metalsa Roanoke

Materials Testing: fatigue (Metalsa)

Strain Amplitude → 2000$\mu\varepsilon$ to 5500$\mu\varepsilon$

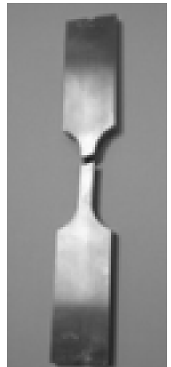
MET1123 Heat-Treated Steel Low-Cycle Results

Specimen Number	Strain Amplitude Plastic
LCF-1	0.000000
LCF-2	0.000000
LCF-3	0.000000
LCF-4	0.000000
LCF-5	0.000100
LCF-6	0.000000
LCF-7	0.000050
LCF-8	0.000400
LCF-9	0.000400
LCF-10	0.000200
LCF-11	0.000700
LCF-12	0.000800
LCF-13	0.000900
LCF-14	0.000800
LCF-15	0.001150
LCF-16	0.001050
LCF-17	0.001200
LCF-18	0.001100
LCF-19	0.001250
LCF-20	0.001400
LCF-21	0.001400
LCF-22	0.001500
LCF-23	0.001600
LCF-24	0.001750
LCF-25	0.002300
LCF-26	0.001700
LCF-27	0.001950
LCF-28	0.002100
LCF-29	0.002200
LCF-30	0.001700

120XF Ultra High Strength Steel Low-Cycle Results

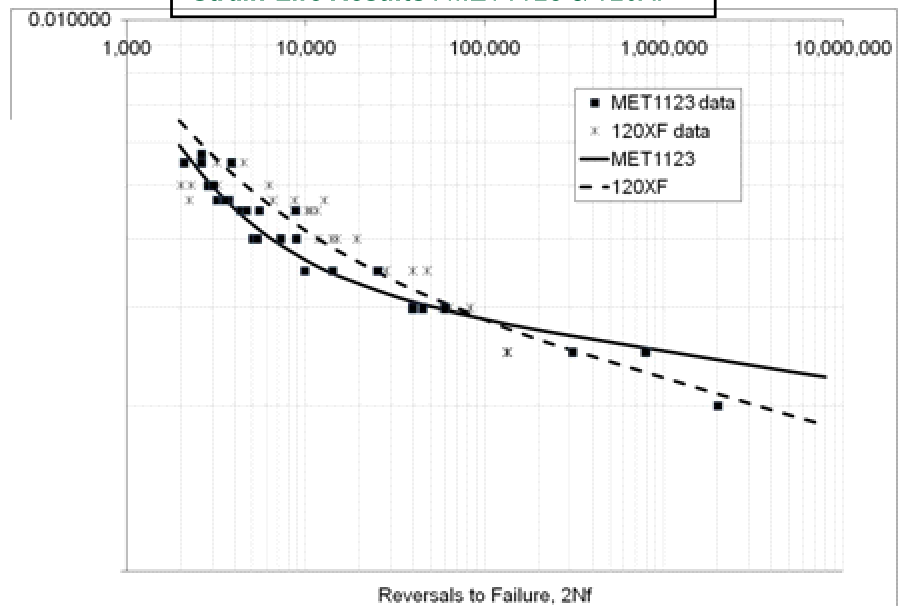
Specimen Number	Strain Amplitude Plastic	Elastic	Total	Cycles Nf	Rev. 2Nf
LCF-1	0.000050	0.001950	0.002000	1,000,000	2,000,000
LCF-2	0.000000	0.002000	0.002000	1,000,000	2,000,000
LCF-3	0.000050	0.002450	0.002500	67,242	134,484
LCF-4	0.000100	0.002400	0.002500	66,456	132,912
LCF-5	0.000150	0.002850	0.003000	41,547	83,094
LCF-6	0.000150	0.002850	0.003000	31,804	63,608
LCF-7	0.000200	0.002800	0.003000	28,857	57,714
LCF-8	0.000350	0.003150	0.003500	14,061	28,122
LCF-9	0.000350	0.003150	0.003500	19,835	39,670
LCF-10	0.000300	0.003200	0.003500	23,869	47,738
LCF-11	0.000750	0.003250	0.004000	7,016	14,032
LCF-12	0.000750	0.003250	0.004000	7,486	14,972
LCF-13	0.000650	0.003350	0.004000	9,628	19,256
LCF-14	0.000700	0.003300	0.004000	5,900	11,800
LCF-15	0.001050	0.003450	0.004500	5,802	11,604
LCF-16	0.001100	0.003400	0.004500	4,316	8,632
LCF-17	0.001000	0.003500	0.004500	5,358	10,716
LCF-18	0.001050	0.003450	0.004500	5,123	10,246
LCF-19	0.001200	0.003500	0.004700	3,277	6,554
LCF-20	0.001200	0.003500	0.004700	4,338	8,676
LCF-21	0.001100	0.003600	0.004700	1,123	2,246
LCF-22	0.001200	0.003500	0.004700	6,379	12,758
LCF-23	0.001550	0.003450	0.005000	1,615	3,230
LCF-24	0.001450	0.003550	0.005000	1,010	2,020
LCF-25	0.001400	0.003600	0.005000	3,138	6,276
LCF-26	0.001500	0.003500	0.005000	1,150	2,300
LCF-27	0.001900	0.003600	0.005500	2,258	4,516
LCF-28	0.001950	0.003550	0.005500	1,601	3,202
LCF-29	0.001900	0.003600	0.005500	1,943	3,886
LCF-30	0.002050	0.003450	0.005500	1,276	2,552

***LCF Fatigue Results** : MET1123 & 120XF – ASTM E606*



Typical LCF Test Specimen

***Strain-Life Results** : MET1123 & 120XF*



Strain-Life Equation
(Coffin-Manson)

$$\Delta\varepsilon/2 = \sigma_f'/E(2N_f)^b + \varepsilon_f'(2N_f)^c$$

Grade	σ_f'/E	b	ε_f'	c
MET1123	.00506	-0.051	4.662	-0.994
120XF	.00755	-0.089	0.761	-0.743

Strain-Life Coefficients & Exponents)

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User Project with Metalsa Roanoke

Hole Making Methods and Parameters

Punch – Soenen 225 Ton hydraulic punch press. Solid ejector-style punch without taper and Firex™ coating. Stroke cycle : 0.6 seconds.

NC Drill – Mazak Super Velocity Center (SVC) 2000L/120. Drill speed 907 rpm (for 27mm drill bit). Carbide indexable drill bit used with Ultrakol 206 water soluble coolant.

CO_2 Laser - Laserdyne Beamdirector 790XL with a 4000 watt CO_2 PRC Laser. Cutting gas is O_2, feed rate is 1500 mm/min. Laser head has 7.5 in focal length.

O_2 Plasma – Hypertherm HT2000 with cutting speed of 140 in/min and 4mm standoff. Cutting gas is Oxygen and air is shield gas.

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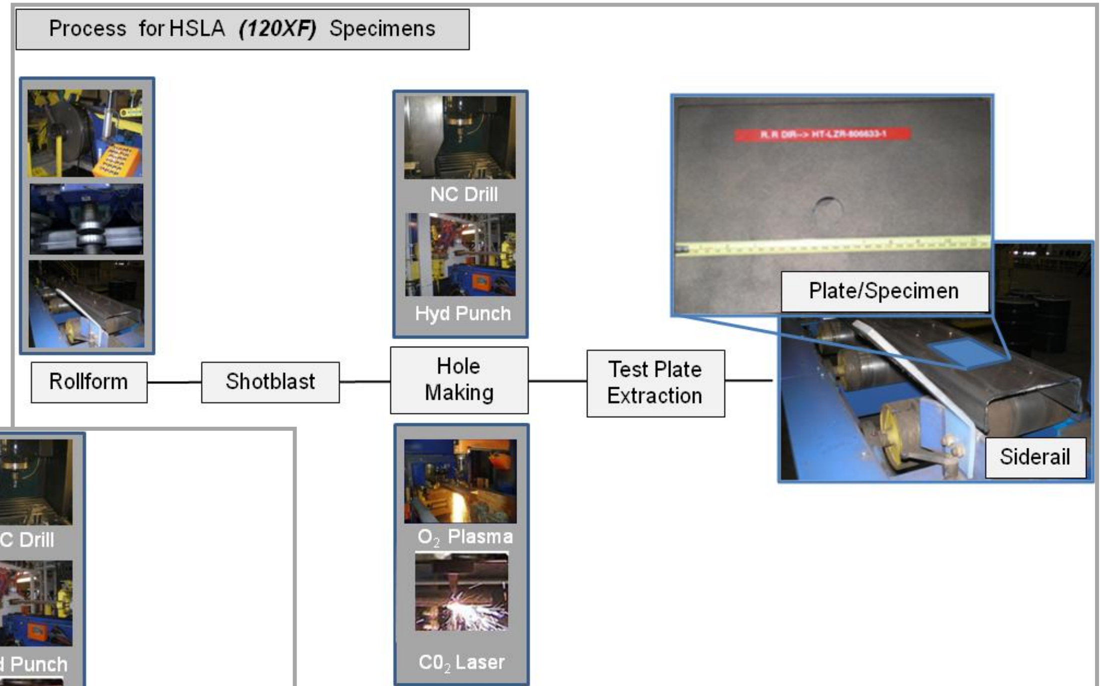
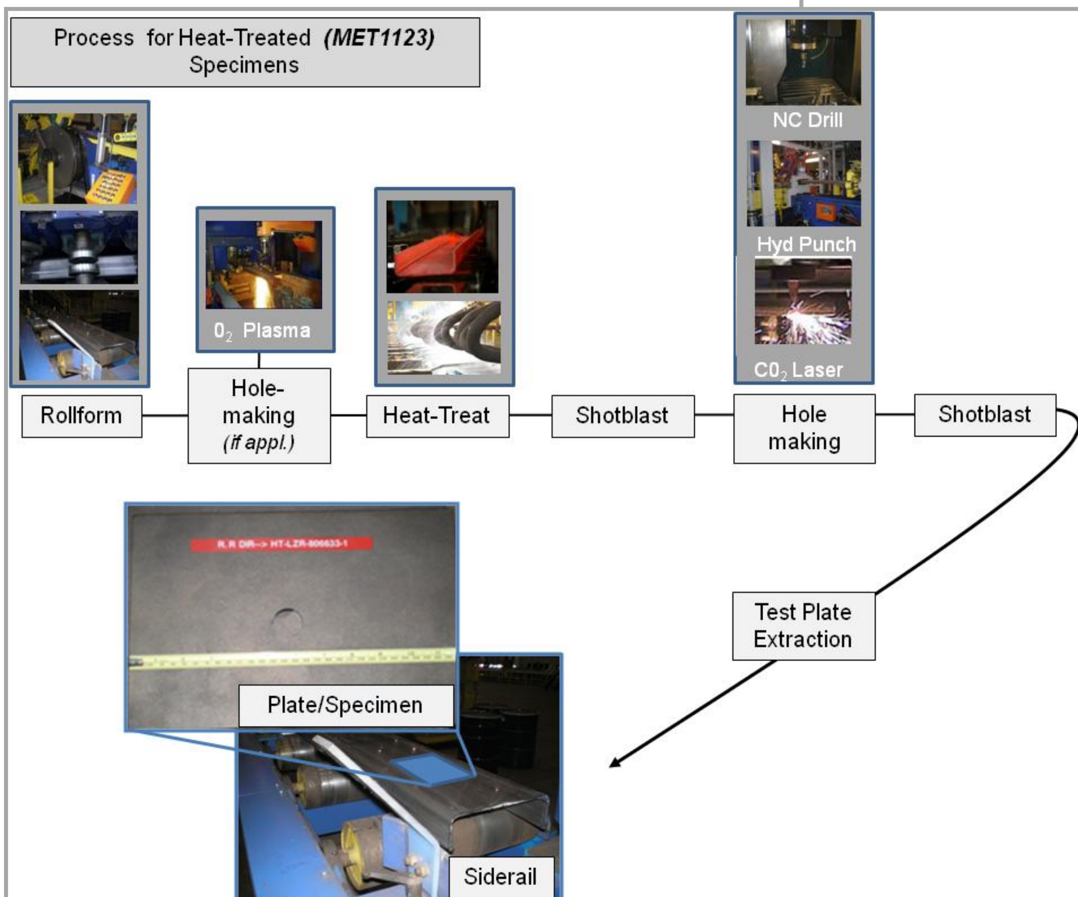
User Project with Metalsa Roanoke

Specimen Process Flow:





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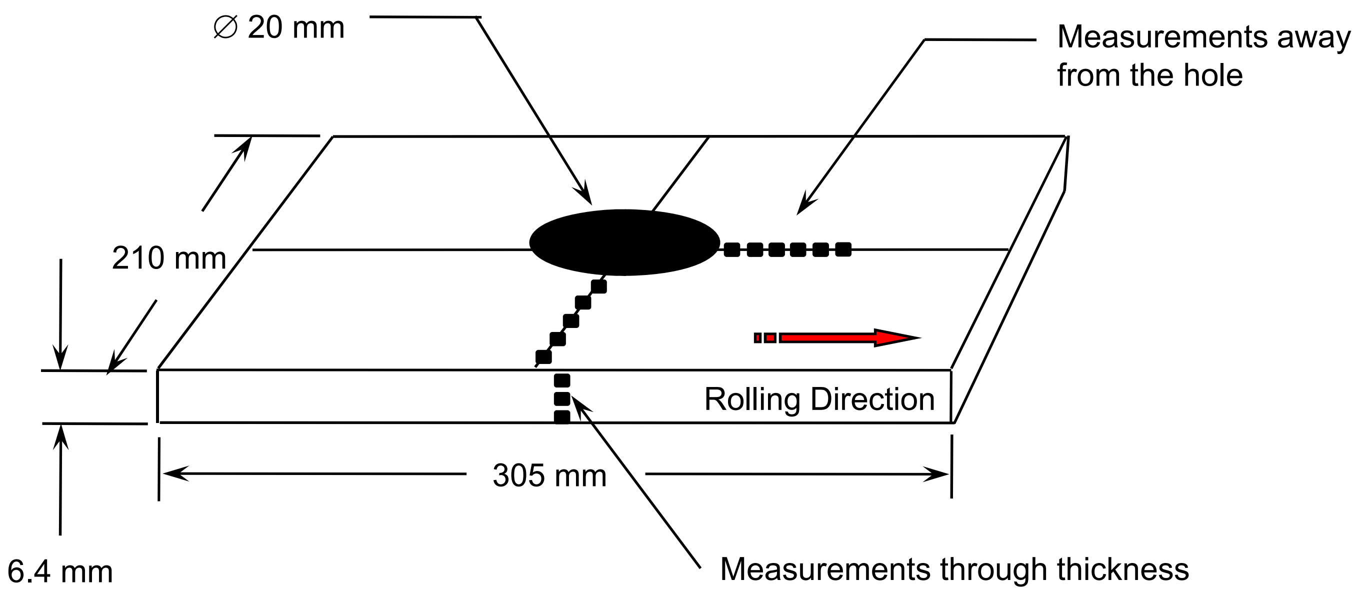
User Project with Metalsa Roanoke

Near Hole Residual Stresses

Measurements in the 8 mm thick steel plates were taken through thickness and along a radial line at 1 mm spacings from the hole edge.



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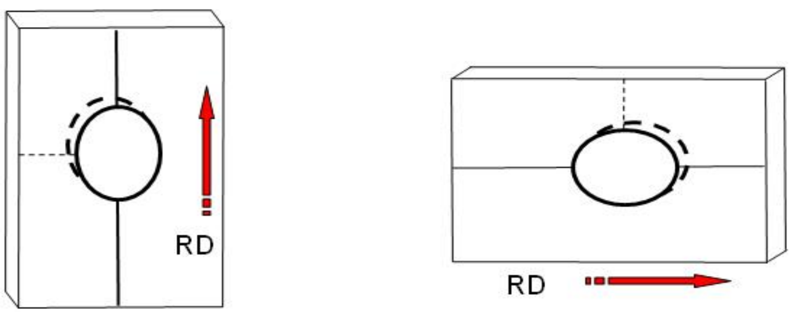
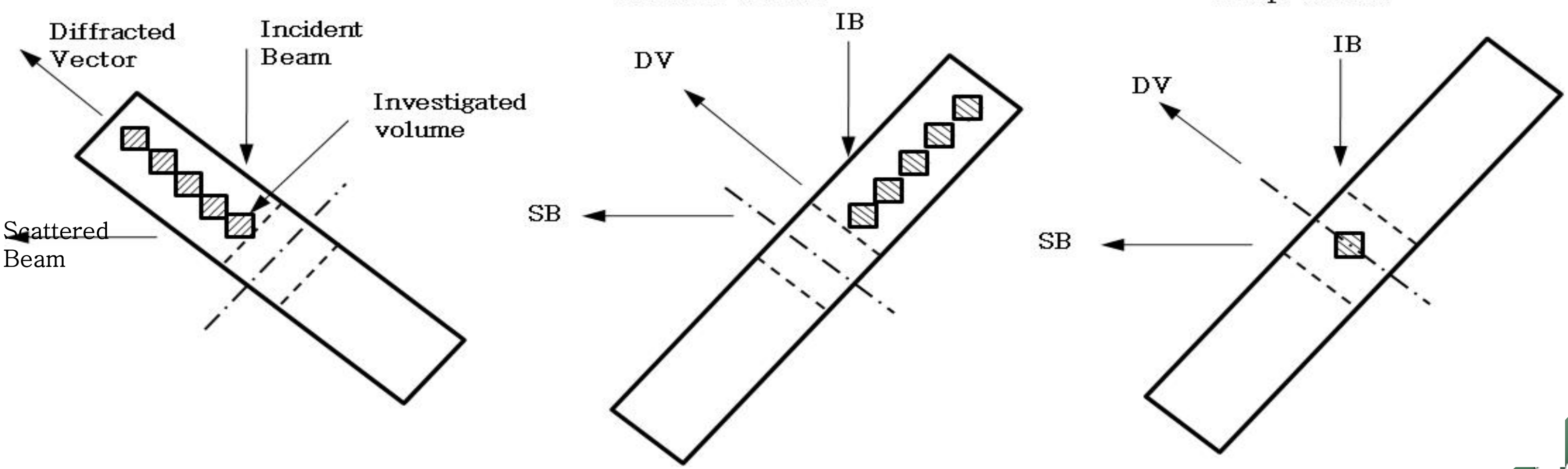
Near Hole Residual Stresses:

Measurements using the neutron diffraction stress mapping method were taken for the radial, normal and hoop strain directions at each of the mapping locations.

Schematic Diagram



Radial Stress | Normal stress | Hoop Stress



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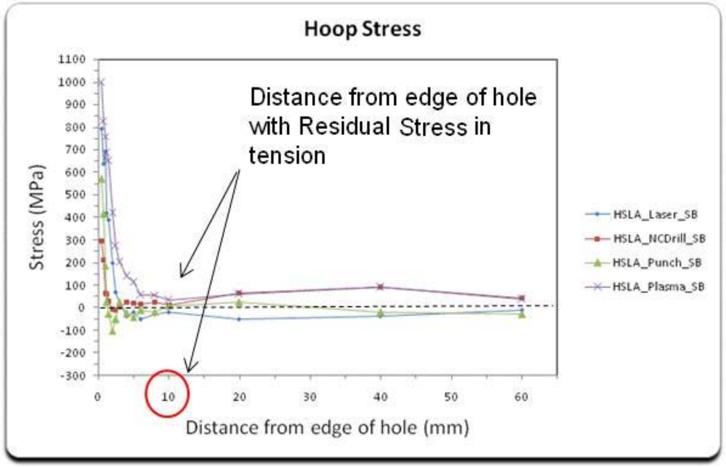
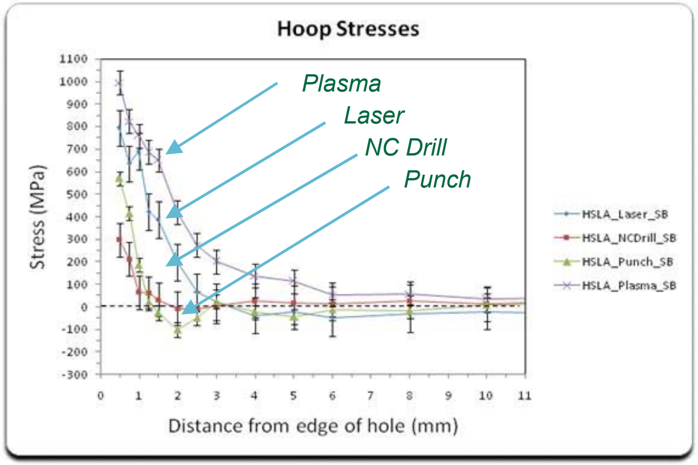
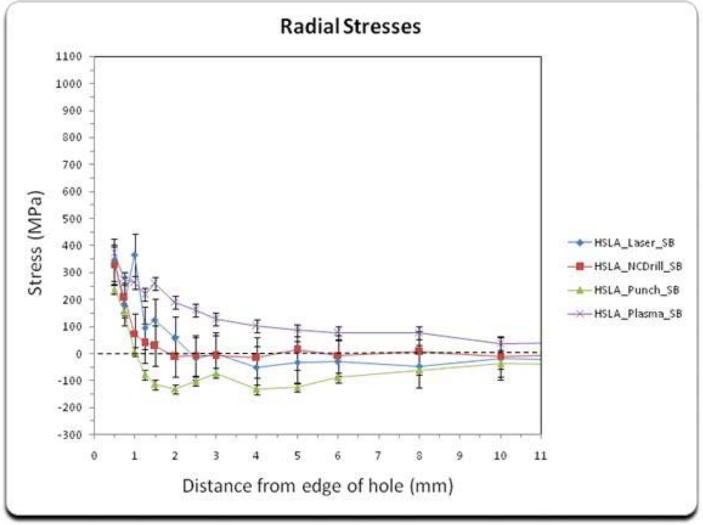
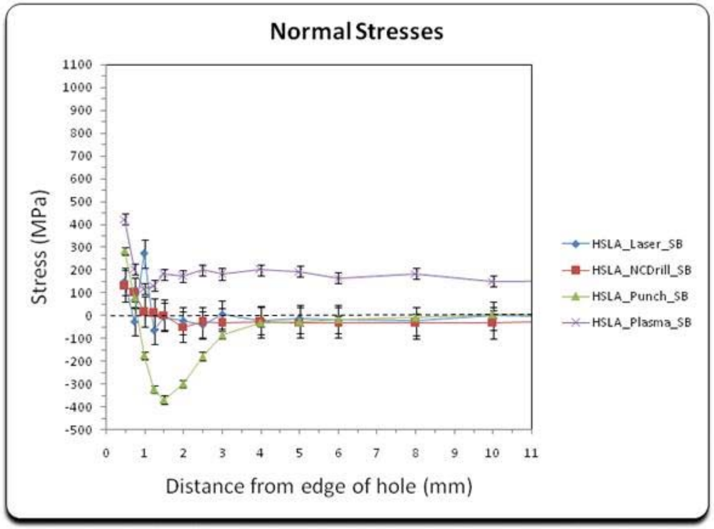
User Project with Metalsa Roanoke
Near Hole Residual Stresses
120XF (HSLA):









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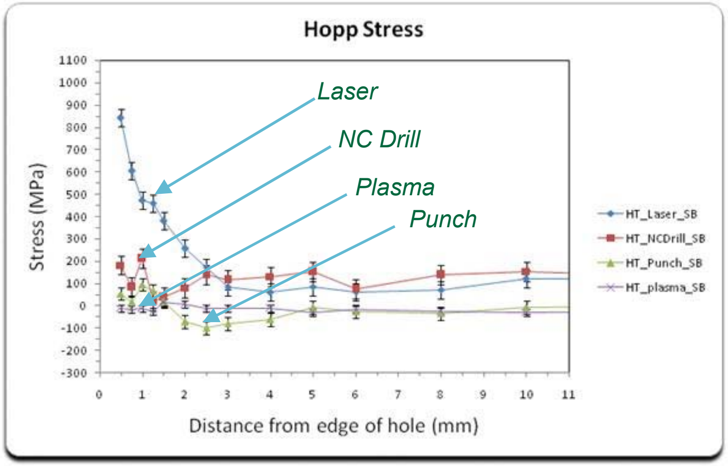
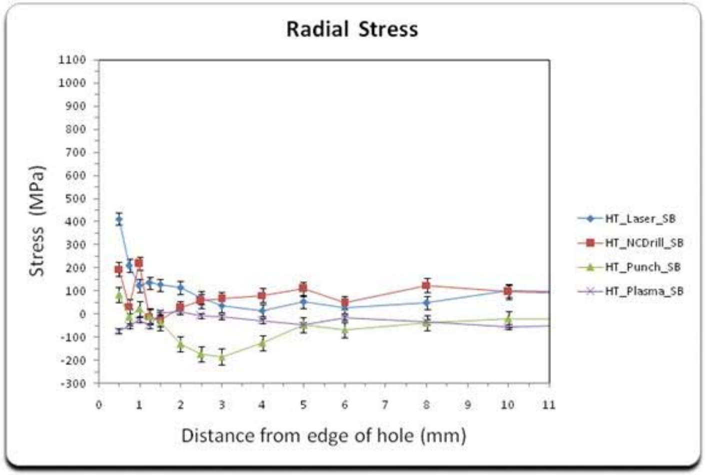
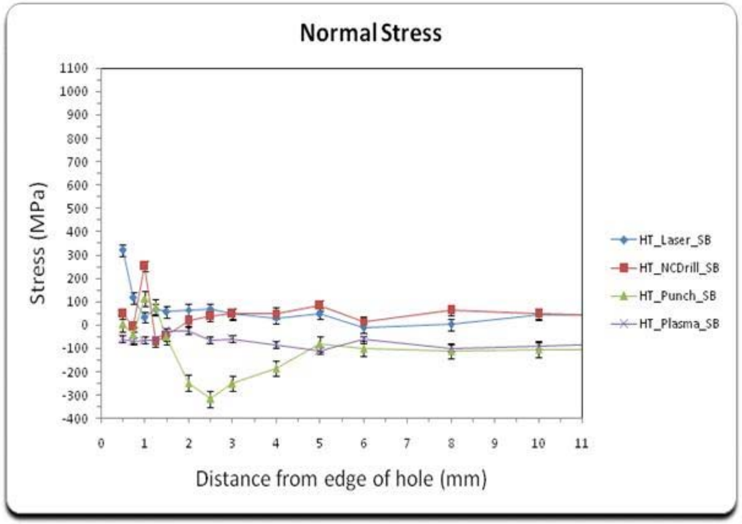
User Project with Metalsa Roanoke

Near Hole Residual Stresses: MET1123







Plasma hole cutting is performed prior to heat-treatment – therefore the heat affected zone is virtually eliminated by subsequent heat treatment – this is evident from above graphs.

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User Project with Metalsa Roanoke

Summary: Near Hole Residual Stresses

- **The hoop direction shows highest tensile stress values for every process.**
- **The highest values of residual stresses in tension were obtained in the HSLA (120XF) with the plasma process and in the MET1123 with the Laser cut process.**
- **Higher stress values occur from thermal processes, explained by kinetics of cooling and change in the microstructure of the material. Confirmed via optical microscope analysis.**
- **Stress measurements were taken from the edge of the hole to 60 mm. Stresses reduced from a maximum value until they were near zero after reaching ~8 mm in each process.**
- **During NC Drilling process, the grains close to the removed section were heated and elongated more than in the bulk of the sample. However, the temperature of the process was not enough to introduce high values of stress, and it appears that plastic deformation could produce the tensile stresses observed in the first 2 millimeters.**
- **The punch process shows the highest compressive stress values, along the normal direction due to mechanical loading, which generally induces compressive stresses.**

Project ID: LMP03, Hubbard

User Project with Metalsa Roanoke

Metalsa Roanoke
"Quality as a way of life"

Results:

- <u>Mechanical processes were more favorable than thermal processes</u> for residual stress fields and resultant fatigue crack growth.
- <u>MET1123 outperforms 120XF</u> for all crack growth and fatigue life estimations regardless of hole process method.
- Tier 1 Testing Facilities and ISO or SAE standards were utilized for all testing:
  - ✓ Westmoreland Materials Testing & Research…….*Monotonic & Fatigue*
  - ✓ HTML at Oak Ridge National Laboratory (ORNL)……….*Residual Stress*
  - ✓ MIRA UK Ltd………………………………………………*Crack Growth*

Project ID: LMP03, Hubbard

Impact of the HTML User Prog Project:

- Evaluated the detrimental effects of manufacturing processes
- Validation of finite element process results with reliable residual stress data underway
- Results guide prevention of detrimental effects of residual stresses
- Developed and evaluated post heat treatments
- Enables avoidance of distortion or cracking in the HAZ during thermal cutting
- Evaluated non-uniform plastic deformation near the hole
- Enables Metalsa to optimize fabrication parameters, process variables and choice of alloys to meet requirements of truck manufacturers

Project ID: LMP03, Hubbard