A/SP Standardization of Hole Expansion Test

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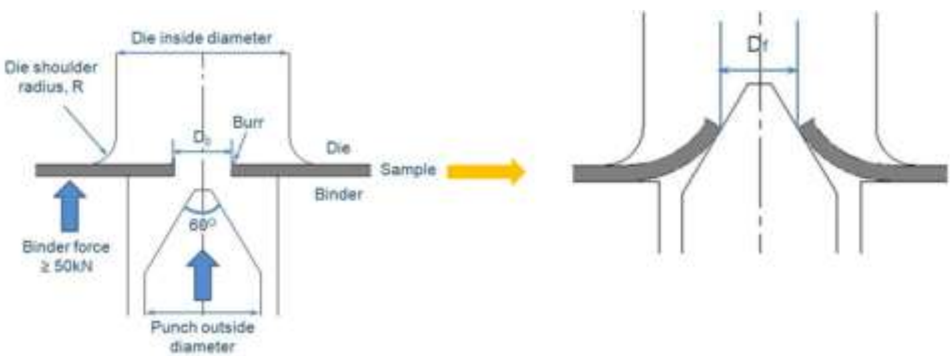
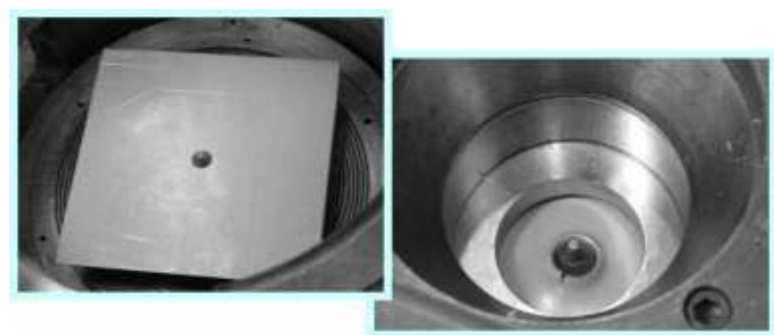
Introduction

- Newly developed AHSS have good ‘Global’ Formability (FLD, elongation, n-value)
- Concerns center around ‘local’ formability
  - ➢ Bendability, ability of bending-under-tension
  - ➢ Stretch flangeability, edge cracking & tearing

Introduction

- Hole expansion test is the most commonly used method to evaluate the AHSS edge cracking resistances. The standards being widely followed are
  - ISO/TS 16630 - 2003
  - JFS T 1001 – 1996
- Large variations exist in the current testing results that hamper the efforts of steel development team and OEMs to reliably evaluate the AHSS performances





$$\text{Hole Expansion Ratio, HER } (\lambda) = \frac{D_f - D_0}{D_0} \times 100$$

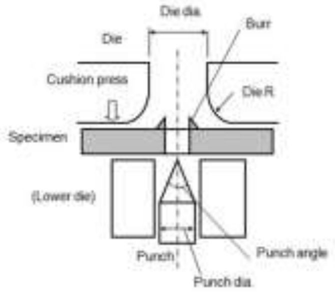
Introduction

- A/SP STHT Team – Chrysler, Ford, GM, AK Steel, ArcelorMittal USA (AM), Nucor, Severstal NA, ThyssenKrupp USA (TKS), USS
- Project objectives
  - Investigate testing variations within a facility and among facilities
  - Minimize testing variations with the standardization and optimization of testing tools, setups and procedure
  - Develop a standard hole expansion test for NA steel and automotive industries
- Phase 1 – Conduct round robin tests for 6 steel suppliers
  - Study 1 – Determine the hole expansion test variations within a facility and among the facilities – 1/2013
  - Study 2 - Determine the hole piercing operation variations – 5/2013
  - Study 3 – Optimize the hole making method to reduce test variations – 10/2013
- Phase 2 – Establish the test standard – 2/2014
- Phase 3 – Standardize / commonize the testing tools, setups and procedure according to the test standard – 12/2014

Study 1: Hole Expansion Test

Sample Preparation	
Specimen	Constant 4"x4"
Hole diameter	Constant Φ10mm
Hole Punching Clearance	Contant 12±2% (t < 2.0 mm)
	Contant 12±1% (t > 2.0 mm)
Punch	Constant 10 mm, M4 tool steel, press fit
Die ring	Constant M2 tool steel, ball lock
Die set	Constant 4 post die
Cutting speed	Constant 60 SPM
Equipment	Constant Mechanical press
Lubrication	Constant None
Testing and Measuring	
Punch angle	Constant 60 degrees
Punch diameter	Noise factor
Tool material	Noise factor
Die radius	Noise factor
Die opening	Noise factor
Tool material	Noise factor
Centering	Noise factor
Binder force	Noise factor
Test speed	Noise factor
Crack definition	Noise factor
Lubrication	Noise factor
Tester	Noise factor
Measurement	Noise factor

Parameter Diagram



Control Factors:
Control all specimen related factors such as: hole diameter, punch die clearance, die wear, die material, hole punching equipment

Input:
Six (6) materials from different suppliers with various microstructures

System
Hole Expansion Test

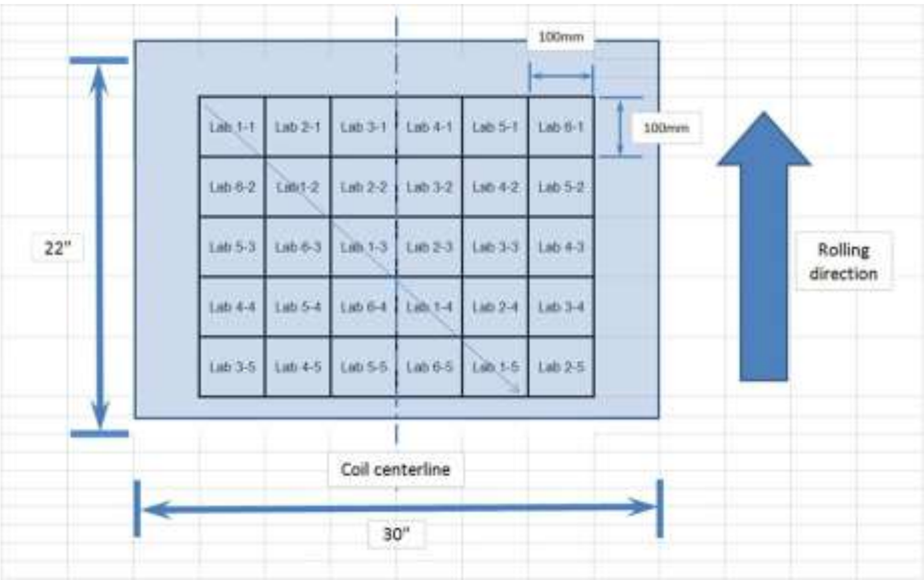
Output:
Hole Expansion Ratio Values/Variation

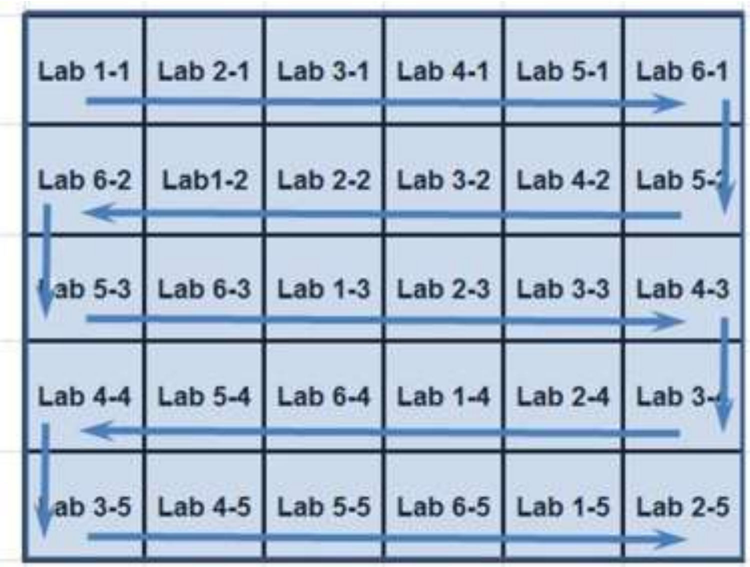
Noise Factors:
Allowed testing parameters to vary such as visual vs computer acquisition of the crack, hole expansion tools and equipment, testing speed, and material type

Symptoms:
Sample cracking on edge of expanded hole

Sampling Control

- Samples were supplied and tested by six (6) steel companies and punched by Lab 2





- Following steel with different coating and microstructures were tested: DP980 GI, DP980 CR, DP590 GI, 780SF HR, 590SF HR, HSLA 420 GI
- 30 samples (4”x4”) were cut from every blank supplied by six participants
- 5 samples were cut across the coil width and length as shown above to reduce die wear effect on hole edges

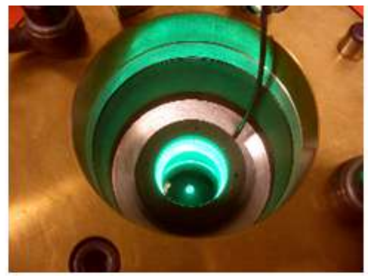
Digital Imaging System vs. Manual Test

- Four(4) participants used digital imaging systems
- Two (2) used manual method.

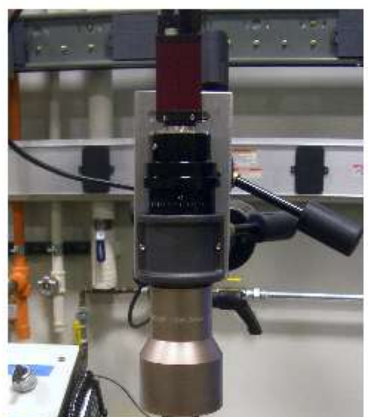
Representative DIS

Opened HE machine

Closed HE machine



Green LED ring light



Telecentric lens & camera

Standard and automated tester

Test Results

Comparisons of 590SF HR and DP980 GI

Sample Name	Test Location	Sample Location Cross the Coil Width						Ave	Std. Dev.	Max Diff
		Left	2nd Left	Middle 1	Middle 2	2nd Right	Right			
HR59	Lab 1	85	72	93	87	90		85	8	21
	Lab 2		110	70	77	77	82	83	16	41
	Lab 3	81		74	79	65	90	78	9	25
	Lab 4	79			86	82		82	4	7
	Lab 5	55	64	73		58	74	65	8	19
	Lab 6	87	93	79	92		106	91	10	27
	Average	77	85	78	84	74	88			
	Std. Dev.	13	21	9	6	13	14			
	Max Diff	32	46	23	15	32	32			
DP98G	Lab 1	23	20	22	22	22		22	1	3
	Lab 2		21	23	26	25	25	24	2	5
	Lab 3	15		18	14	17	17	16	1	3
	Lab 4	24	25		21	24	22	23	2	4
	Lab 5	23	17	18		24	20	20	3	8
	Lab 6	23	22	23	22		24	23	1	2
	Average	22	21	21	21	22	21			
	Std. Dev.	4	3	3	4	3	3			
	Max Diff	9	8	6	11	8	8			

- The average HER values vary noticeably among the testing labs than those for the coil locations – more testing variations than material variations
- The standard deviations are smaller for each individual lab than for all labs – labs are more consistent with themselves than each other

Result Analysis

Comparison of Revised Average HER

Ranking	Ranking for Average HER of Revised Results											
	HS42		DP98B		HR59		DP59G		HR78		DP98G	
1	48	Lab 1	23	Lab 2	91	Lab 6	35	Lab 1	85	Lab 2	24	Lab 2
2	46	Lab 6	20	Lab 1	87	Lab 1	34	Lab 2	83	Lab 6	23	Lab 4
3	45	Lab 4	19	Lab 4	82	Lab 4	32	Lab 4	77	Lab 4	23	Lab 6
4	40	Lab 2	18	Lab 6	78	Lab 2	30	Lab 6	76	Lab 1	22	Lab 1
5	39	Lab 5	17	Lab 5	78	Lab 3	30	Lab 3	70	Lab 5	20	Lab 5
6	38	Lab 3	15	Lab 3	65	Lab 5	23	Lab 5	68	Lab 3	16	Lab3

Material	Ranking for Average HER of Revised Results					
	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6
HS42	1	4	6	3	5	2
DP980B	2	1	6	3	5	4
HR59	2	4	5	3	6	1
DP59G	1	2	5	3	6	4
HR78	4	1	6	3	5	2
DP98G	4	1	6	2	5	3
Score	14	13	34	17	32	16
Ranking	2	1	6	4	5	3

Comparison of Revised Standard Deviation

Ranking	Ranking for Standard Deviation of Revised Results											
	HS42		DP98B		HR59		DP59G		HR78		DP98G	
1	0.8	Lab 2	0.0	Lab 4	2.5	Lab 1	0.6	Lab 1	1.9	Lab 3	0.0	Lab 1
2	1.0	Lab 3	0.1	Lab 6	2.9	Lab 2	0.7	Lab 4	3.4	Lab 2	0.7	Lab 6
3	2.7	Lab 5	0.6	Lab 1	3.5	Lab 6	0.9	Lab 2	3.9	Lab 5	1.2	Lab 4
4	3.2	Lab 1	0.9	Lab 2	3.5	Lab 4	2.0	Lab 3	5.0	Lab 6	1.2	Lab 3
5	4.0	Lab 4	1.5	Lab 3	3.8	Lab 3	2.2	Lab 6	5.3	Lab 1	1.3	Lab 2
6	6.8	Lab 6	1.7	Lab 5	7.2	Lab 5	2.7	Lab 5	10.8	Lab 4	2.2	Lab 5

Material	Ranking for Standard Deviation of Revised Results					
	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6
HS42	4	1	2	5	3	6
DP980B	3	4	5	1	6	2
HR59	1	2	5	4	6	3
DP59G	1	3	4	2	6	5
HR78	5	2	1	6	3	4
DP98G	1	5	4	3	6	2
Score	16	17	21	21	30	22
Ranking	1	2	4	4	6	5

- Average HER values obtained by the digital imaging systems and manual methods are comparable
- Digital imaging system results show better objectivity and consistency
- Findings represent small sample populations, and need to be verified with the round robin test with large sample populations

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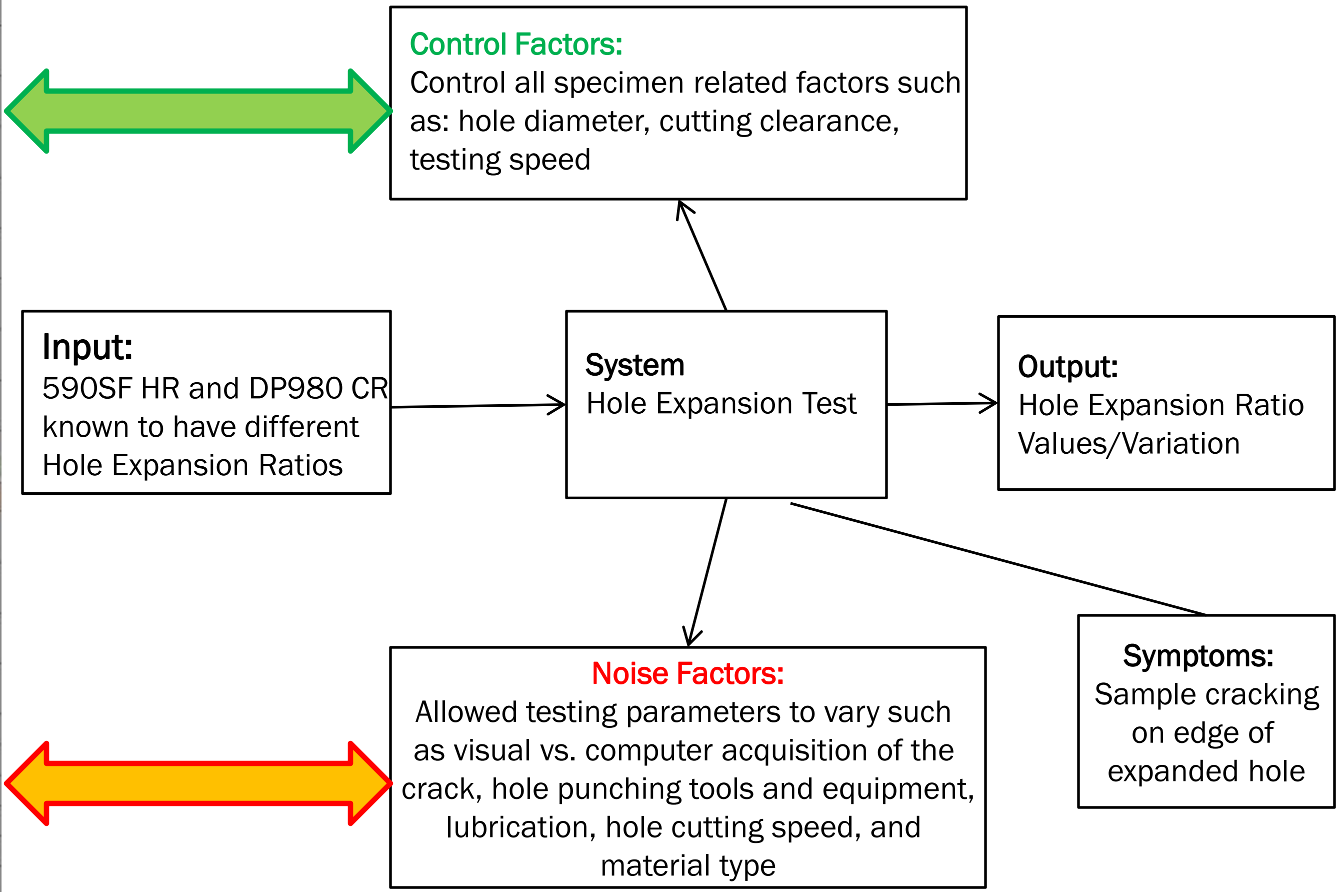
Study 2: Hole Piercing Operation

Testing and Measuring	
Punch angle	Constant 60 degrees
Punch diameter	Constant 40 mm
Tool material	Constant Carbide
Die radius	Constant 8mm
Die opening	Constant 44 mm
Tool material	Constant Hardened D2 steel
Centering	Constant Self centering
Binder force	Constant 310 kN
Test speed	Constant 0.2mm / second
Crack definition	Constant 0.1mm±0.03mm
Lubrication	Constant None
Tester	Constant MTS 866.51 metalformer
Measurement	Constant Fitting circle to the images expanded
Sample Preparation	
Specimen	Constant 4"x4"
Hole diameter	Constant Φ10mm
Hole Punching Clearance	Constant 12±2% (t < 2.0 mm)
	Constant 12±1% (t > 2.0 mm)
Punch	Noise factor
Die ring	Noise factor
Die set	Noise factor
Cutting speed	Noise factor
Equipment	Noise factor
Lubrication	Noise factor

Parameter Diagram



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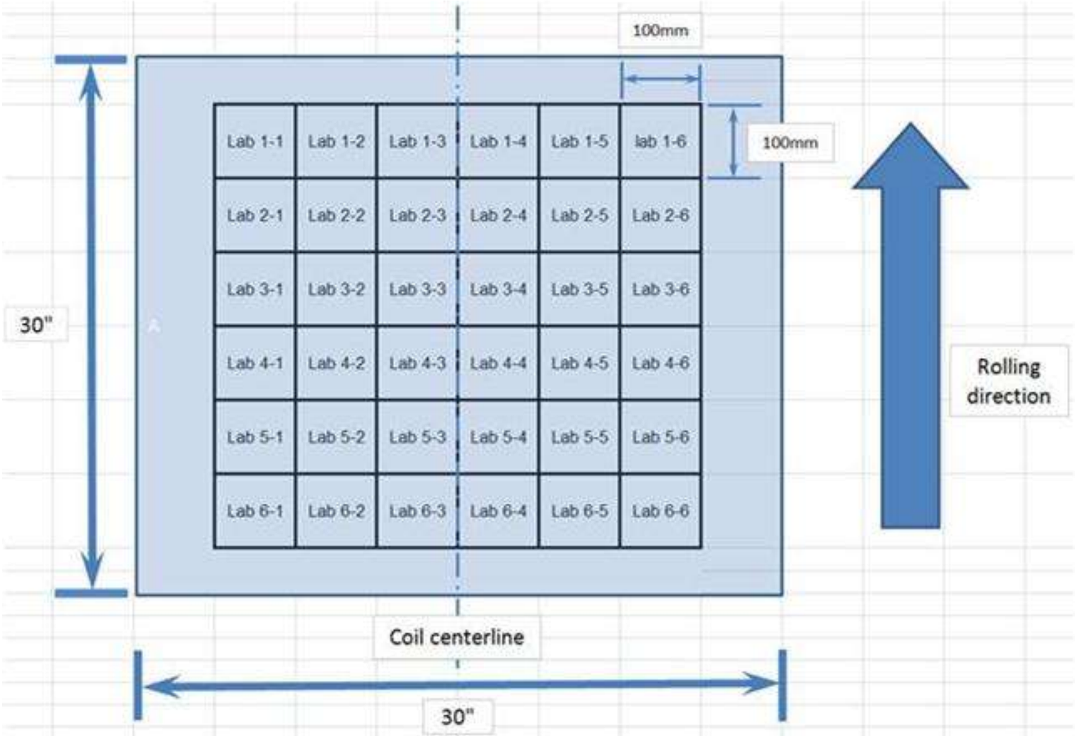
Sampling Control

- Samples were supplied by Lab 2, punched by all participants and tested by Lab 2 (with DIS) and Lab 3 (with manual method)



- 36 samples were cut
  - from the same sheet of 590SF HR and DP980 CR, respectively
  - across the coil width and length with a similar technique used in study 1

Hole Punching Equipment and Tools

A/SP Round Robin Hole Expanding Test (4-2013)

	ISO	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6
	Specifications	Specifications	Specifications	Specifications	Specifications	Specifications	Specifications
Specimen							
Dimension (mm)	Aim 150 x 150	4" x 4"	4" x 4"	4" x 12"-15" (3 holes)	4" x 4"	4" x 4"	3.5" x 3.5"
Thickness (mm)	1.2 to 6.0	Any	0.4 to 6.0	1.0-6.0			
Punching							
Hole diameter (mm)	Φ10	10	Φ10	Φ10	Φ10	Φ10	Φ10
Clearance	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)
	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)
Tooling							
Punch	Not specified	10 mm, A2 tool steel	10 mm, M4 tool steel	Unipunch	10 mm, M4 tool steel	10 mm, S5 tool steel (center pin)	10mm, M4 tool steel
Die	Not specified	Variable, A2 tool steel	Variable, M2 tool steel	Unipunch	Variable, M2 tool steel	Variable, S5 tool steel	Variable, M4 tool steel
Tooling Type	Not specified	4 post piercing die	4 post piercing die	C-clamp	4 post piercing die	None	C - clamp
Process control							
Type	Not specified	Hydraulic press	Mechanical press	Hydraulic press	Mechanical press	Hydraulic press	Hydraulic press
Cutting speed	Not specified	v ≅ 25 mm/sec	v ≅ 124 mm/sec		v ≅ 76 mm/sec	v ≅ 10 mm/sec	v ≅ 6.2 mm/sec
Lubrication	Not specified	None	None	None	None	None	Mill oil
Lubrication vol	Not specified	None	None	None	None	None	A drop

- The differences in the lab hole punching equipment and tools are identified
  - Press – mechanical, hydraulic; varying cutting speeds
  - Dies – 4-posts, 2-post, C type; various tool steels
  - Method – lubed, without lubrication

Test Results

Comparisons of Results of Different Labs

HR590SF	Hole Testing		Average HER		Standard Deviation	
			Lab 2	Lab 3	Lab 2	Lab 3
	Hole Punching	Lab 1	94	89	19	16
		Lab 2	82	86	11	15
		Lab 3	79	76	12	17
		Lab 4	84	94	15	5
		Lab 5	76	83	13	16
		Lab 6	77	76	9	14
	Average		**83**	**86**	**14**	**14**
	Standard Deviation		**7**	**7**		

DP980	Hole Testing		Average HER		Standard Deviation	
			Lab 2	Lab 3	Lab 2	Lab 3
	Hole Punching	Lab 1	22	29	1	3
		Lab 2	19	18	2	1
		Lab 3	24	23	2	4
		Lab 4	18	24	2	3
		Lab 5	20	21	3	2
		Lab 6	19	26	1	3
	Average		**20**	**23**	**2**	**3**
	Standard Deviation		**2**	**4**		

- Two different test methods (DIS - Lab2 and manual – Lab3) were used in the tests for comparison
- Noticeable differences in HER results were found for samples punched by different labs
- No clear trend is found for different hole punching operations
- Comparing with the manual test results, the digital imaging system has generated the HER results with less variations

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Study 3: Optimization of Hole Making Methods

Hole punching equipment

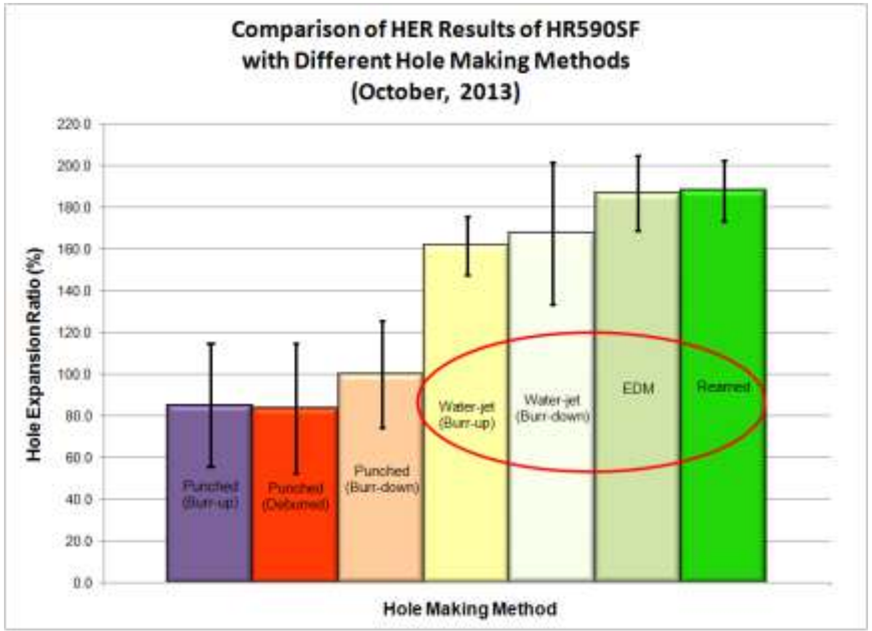
Water-jet cutting equipment

EDM equipment

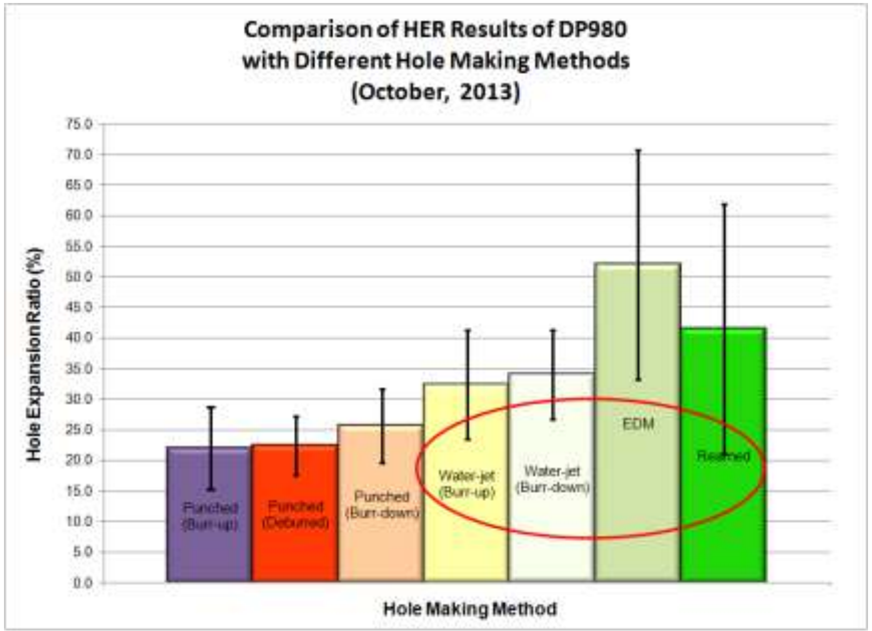
Reaming equipment

Test Results

HER Variations for Different Edge Conditions



HR590SF



DP980

- As expected, the HER values of water-jet cut, EDM and reamed holes are better than punched holes
- Best results seem to be from the punched holes tested with burr down condition

Failure Modes and Edge Conditions

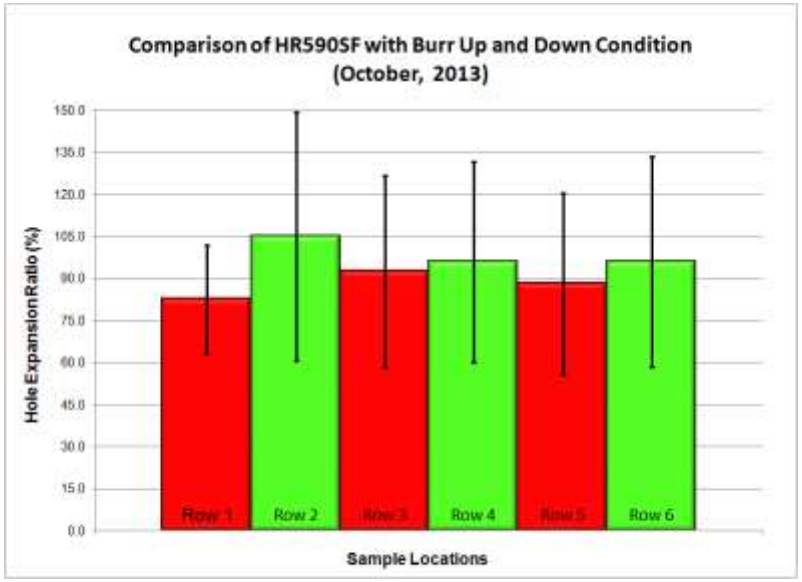
- The HER variations are smaller for high HER value samples with water-jet cut, EDM and reamed holes
- Because of surface friction and large contact areas, the samples with high expansions were stuck on the punch. The punch had to be pressed out after each test
- Instead of cracking, the edges appear failing by splitting or necking. The holes are not circular and the shapes seem to be affected by the steel anisotropy

Edge Conditions and Test Variations

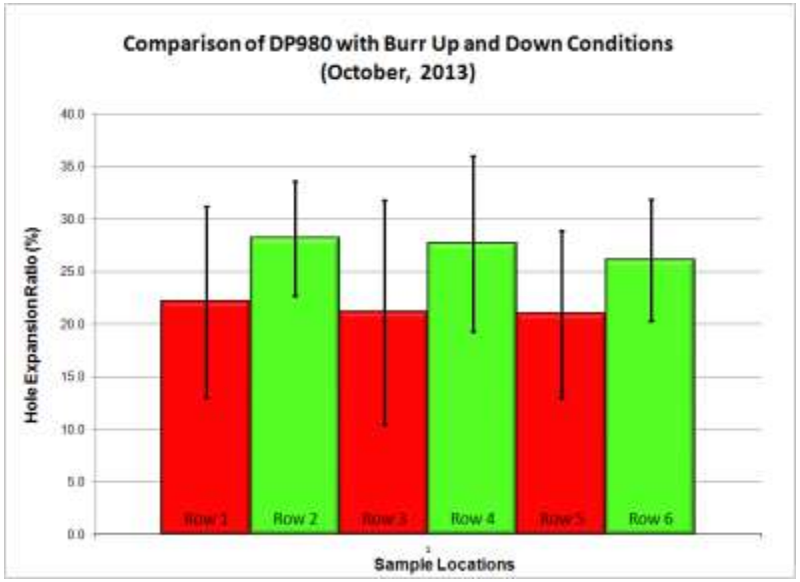
- The edge conditions may change the failure mode from edge cracking to edge necking / splitting – an FLC type of failure
- The good edge conditions can improve the HER results. However, they do not necessarily reduce the HER variations because of the material variability / inhomogeneity
- The low HER values and variations had been obtained for the holes with run down edge conditions. In this case, the edge conditions resulting from the process have dominated the edge cracking performances
- By intuition, a "sweet spot" can exist for minimized HER variations. It would be difficult to realize it by matching the hole making methods with the materials

Testing Conditions and Variations

Variations of HER



HR590SF



DP980 CR

- A set of 60 punched samples was tested with burr up and down conditions to verify the previous test
- Burr down (Green)produces better HER values
- The variations are not consistent. Less variation is found for burr up tests of 590SF HR. For DP980 CR, it is opposite

Auto/Steel Partnership

A/SP Hole Expansion Test Method

	ISO	ASP
	Specifications	Specifications
Specimen		
Dimension (mm)	Aim 150 x 150	100 x 100
Thickness (mm)	1.2 to 6.0	0.4 to 6.0
Quantity		
Regular	> 3	> 5
Qualification	No specification	> 45
Punching		
Hole diameter (mm)	Φ10	Φ10
Clearance	12±2% (t < 2.0 mm)	12±2% (t < 2.0 mm)
	12±1% (t ≥ 2.0 mm)	12±1% (t ≥ 2.0 mm)
Tooling		
Punch	No specification	M4/M2 tool steel
Die	No specification	M4/M2 tool steel
Tooling Type	No specification	Four (4) post die
Testing		
Specimen Positon / Burr Direction	Up / away from punch	Up / away from punch
Punch		
Angle (degree)	60 ± 1	60 ± 1
Diameter (mm)	No specification	> 40
Material	No specification, HRc ≥ 55	Carbide, R_a ≤ 0.8
Die		
R (mm)	≤ 20 (aim to 5)	5
Dia (mm)	≥ 40	52 ± 2
Material	Not specified	Tool steel, HRc ≥ 55
Blank Holder Force	≥ 50kN	≥ 50kN
Test Speed	≤ 1.0mm/s	0.2 mm/sce
Process Control	Visual	Visual / Camera
Test Termination	Thru thickness crack	Thru thickness crack with width = 0.1mm ± 0.03mm
Measuring		
Measurement	Caliber with resolution of 0.05mm	0.05mm / Curve fitting
HER determination	Ave of 0 and 90 degree	Ave of 0 and 90 degree. Curve fitting

On the basis of round robin test results and ISO standard, A/SP proposes a hole expansion test method to reduce the testing variations

Conclusions

- Edges can fail in two different modes (cracking or necking /splitting) in hole expansion tests depending on the material properties and cut edge conditions
- Results show that the testing variations can be larger than the AHSS material variations
- Testing variations among the labs are bigger than these within a lab
- The digital imaging system should be used for the hole expansion test because of its objectivity and consistency in inter-laboratory tests
- The hole piercing operation has a significant effect on HER variation
- The effects of hole piercing and expansion operations are entangled intrinsically and difficult to separate
- Some hole making methods have improved the HER values significantly. They do not necessarily reduce the variations
- We should minimize the testing variations. The HER results will still be affected by the material variations because of AHSS inhomogeneous microstructures

For More Information

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